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APPLICATION OF INTERFEROMETRIC SYNTHETIC APERTURE RADAR DATA IN ASSESSING LAND SUBSIDENCE RESULTING FROM HUMAN FACTORS IN NINH BINH PROVINCE, VIETNAM

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Abstract

The method of Satellite Interferometric Synthetic Aperture Radar, based on analyzing the phase difference of radar complex images recorded from two different positions simultaneously observing a terrain area where the signals have the same amplitude, frequency, and wavelength but different phases, the deformation of the terrain surface in Ninh Binh province is analyzed and calculated. The preliminary results include the construction of a deformation map of the ground surface in the Ninh Binh province for the period 2020 - 2021, consisting of 78,077 points. The map shows areas that have been uplifted with values of 3 - 5 mm/year and >5 mm/year, particularly highlighting areas with significant subsidence velocities of <-10 mm/year (Kim Son and Yen Khanh districts), some areas with subsidence velocities ranging from -5 to -10 mm/year (Yen Nhan commune, Yen Mo district, Nam Binh ward, Ninh Phong district in Ninh Binh city), and subsidence values of 0 to -5 mm/year in the communes bordering between Nho Quan and Gia Vien districts. These results provide a basis for identifying the causes of terrain surface changes and proposing solutions to prevent and mitigate damages in Ninh Binh province; In-depth studies will continue.

Keywords: Interferometric Synthetic Aperture Radar; Surface deformation; Uplifted; Subsidence; Ninh Binh.

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1. Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique widely used in the study of terrain changes both globally and in Vietnam. By analyzing the phase differences of radar signals collected by satellites over time, InSAR can detect and measure subtle surface movements. It has been applied in various domains including geology,

environmental monitoring, and urban planning. In the global context, InSAR has provided valuable insights into tectonic movements, volcanic activities, and land subsidence in regions prone to natural hazards [1, 2, 3, 4]. Alex Hay-Man Ng. (2012) discussed the use of InSAR to monitor land subsidence in Jakarta, a city prone to significant ground deformation [5]. Muhammad Afaq Hussain (2022) used the Persistent Scatterers In-SAR technique for monitoring land subsidence in a coastal city in Pakistan [6].

In Vietnam, InSAR has been instrumental in monitoring land subsidence in the Mekong delta region due to groundwater extraction and understanding the deformation of the Red River delta [7]. Additionally, other studies such as the project "Research on the scientific basis and propose solutions for predicting ground subsidence in Hanoi city using interferometric radar techniques" code DTDL.2012-T/28, led by the Institute of Geology [17], applied Alos-Palsar images from 2007 - 2011 and Cosmo-Skymed, TerraSAR-X images from 2011 - 2014 using interferometric radar methods to study surface deformation in the central area of Hanoi. The study identified high subsidence areas such as Hoang Cau, Ha Dong, Tan Mai, Phap Van - Linh Dam, and widespread subsidence areas like Ha Dinh, Thanh Xuan, and Tan Mai. Notably, in the Tram Troi area, many high-speed subsidence areas with rates < -15 mm/year were detected. Areas with little subsidence, even with positive velocity values (uplift according to radar data), are concentrated in the northern key areas such as Tay Ho district, and Cau Giay district, including Nghia Tan and Nghia Do. The research results from the project "Researching on the scientific basis and proposing the solutions for early warning of landslides, flash floods, mud and rock floods in Northern Vietnam using remote sensing technology and data on geological structure" code VT-UD.05/18-20 [16] have been confirmed in land subsidence studies in the Cam Pha - Quang Ninh area. As a result of Radar interference analysis, it was found that the subsidence area in Cam Pha city center is concentrated in the two districts of Cam Dong and Cam Son districts, and extends beyond the study area to Cua Ong and Mong Duong districts. The average subsidence rate is -3 to -5 mm/year. In these studies, field verification has shown that satellite radar technology using interferometric radar methods allows for the identification of subsidence areas in both spatial and temporal dimensions

From 2019 to now, there have been continuous subsidence incidents in Ninh Binh province. These subsidence incidents always occur on traffic routes and around construction areas [10, 11, 12, 13, 14, 15]. That is the reason, the project "Research on the assessment of land subsidence, ground fissures, and propose solutions for prevention and mitigation of damage in Ninh Binh province", led by a group of scientists at the Institute of Geology, has been proposed for implementation during the period 2022 - 2025. This paper presents the initial results achieved through the use of satellite interferometric radar technology, laying the foundation for more in-depth studies to understand the causes of subsidence in Ninh Binh,

thereby proposing preventive and mitigation solutions for the study area.

2. Methods and materials

2.1. Area research

Ninh Binh is the southernmost province of the North Delta, located between 190°50'N and 200°27'N, 105°32'E and 106°27'E. The Tam Diep mountains run in a Northwest - Southeast direction and form the natural boundary between her two provinces, Ninh Binh and Thanh Hoa. It is surrounded by the Day River to the East and Northeast, borders Ha Nam and Nam Dinh provinces, Hoa Binh province to the North, and the East Sea to the South.

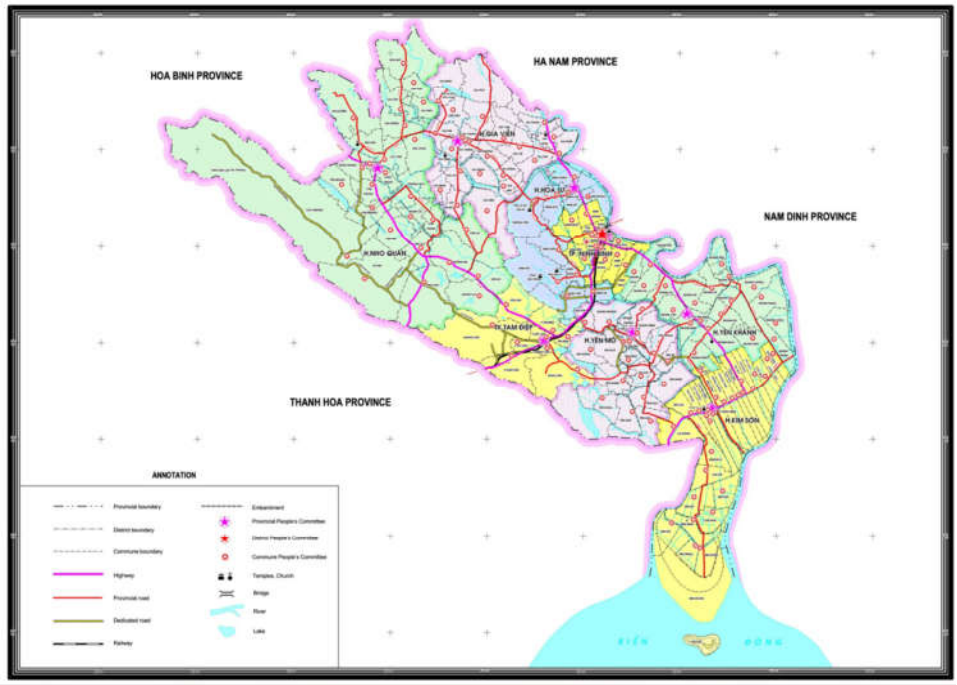


Figure 1: Map of Ninh Binh

Ninh Binh has three distinct regions.

* *Delta region:* occupies 71.1 % of the province's natural area, it is the most densely populated area in the province, home to about 90 % of the province's population. The area has an average elevation of 0.9 - 1.2 m. The land is mainly alluvial

* *Mountainous and Semi-mountainous regions:* This region is located in the Western and Southwestern parts of the provinces. The entire region covers an area of about 35,000 hectares, accounting for 24 % of the state's natural area. The average height is 90 - 120 meters. Somewhere, rocky areas are more than 200 m high. Up to 90 % of the state's mountain and forest area is concentrated in this region.

* *Coastal region:* Ninh Binh has more than 15 km of coastline. Covering an area of about 6,000 hectares, it accounts for 4.2 % of the state's natural area. The land here is still very salty due to new deposits and is currently undergoing refurbishment.

Ninh Binh has a tropical monsoon climate. The annual weather is divided into 4 distinct seasons: Spring, summer,

autumn, and winter. The average annual temperature is about 23 degrees Celsius. The average number of sunshine hours in a year is over 1100 hours. The average rainfall per year is 1,800 mm.

Ninh Binh is an important intersection from the North to the Central and the South with many important roads, railways, and waterways running through. The river system in Ninh Binh includes the system of Day Rive, Hoang Long river, Boi River, An River, Vac River, Lang River, and Van Sang river, with a total length of 496 km, widely distributed throughout the province. The average density of rivers and streams is 0.5 km/ km^2, rivers usually flow in the direction of Northwest - Southeast to empty into the East Sea.

Sentinel-1 data is currently completely free of charge. Within the research area of the project, Sentinel imagery data can be downloaded from the website: https://scihub.copernicus.eu/

The research area images are in VV polarization with an Ascending orbit. The time is from 2014 until now, however, the quantity and the availability of images provided may vary depending on different research areas.

The Sentinel-1 images used in this study are in Interferometric Wide (IW) mode. The data has a swath length of 250 km with a spatial resolution of 5 × 20 m (single-look). The IW mode captures three sub-swaths through the Terrain Observation with Progressive Scans SAR (TOPSAR) scanning technique. With the TOPSAR technique, beam steering is not only controlled in azimuth as in ScanSAR, but also electronically steered in the reverse direction for each acquisition, avoiding misalignment and ensuring image quality consistency throughout the swath [8].

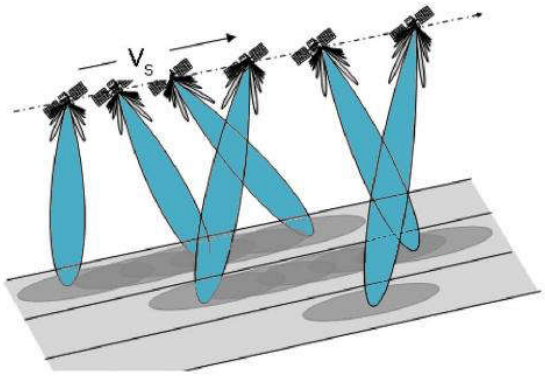


Figure 2: Acquisition mode of TOPSAR Sub-Swath

Each captured image has three vertical IW sub-strips labeled IW1, IW2, and IW3 from right to left. Each IW has 9 - 10 bursts depending on the research area.

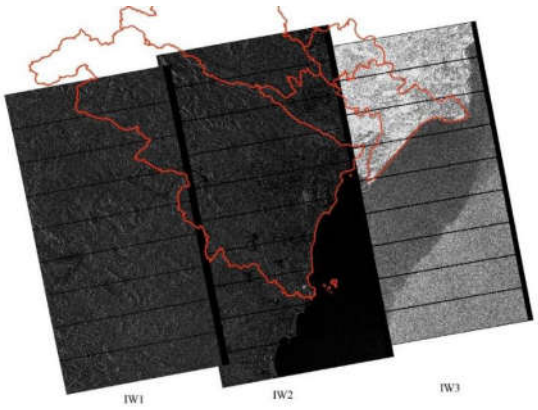


Figure 3: Track and burst information received from Sentinel Ninh Binh province on February 9th, 2020

2.2. Method research

SAR is a special radar imaging technique at high resolution, which uses the motion of a satellite or a carrier to simulate the antenna size (also known as synthetic) to improve the spatial resolution of the imaging radar. Currently,

the SAR technique in photography is used more and more widely in Environmental monitoring, earth-resource mapping, and military systems.

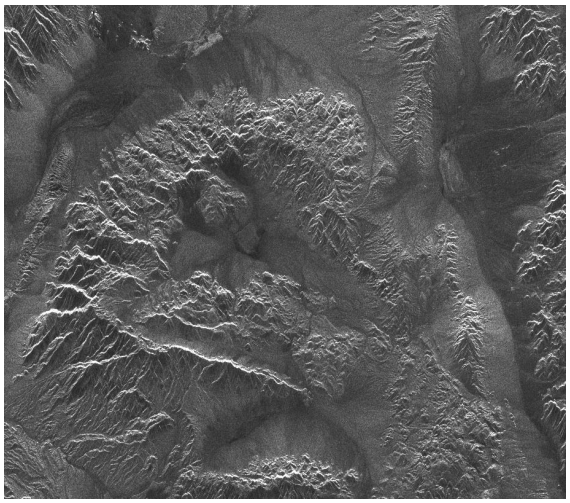


Figure 4: Example of SAR image

SAR data also enables an analytical method called interferometry (InSAR). InSAR uses the phase information recorded by the sensor to measure the distance from the sensor to the target. If at least two observations are made of the same target, the distance from the sensor and the additional geometric information can be used to measure changes in the topography of the earth's surface. These measurements are very accurate to centimeters and can be used to identify areas of deformation. If two or more images are a series of images covering the same area and are used, for example, to determine terrain variation, these images need to be spatially aligned with each other during image registration. In this case, it is resampled to change the relative translation, rotation, and scale (for pixels of different sizes). SAR image interferometry combines two or more complex-valued SAR images and utilizes phase difference values to extract information about image objects. Images used for interference must differ in at least one element (such as the baseline).

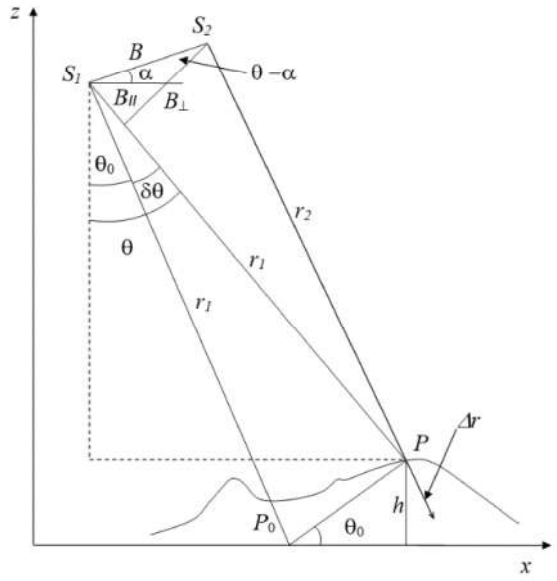


Figure 5: Basics of Interferometric SAR (INSAR)

From the above figure, the phase component depends on the terrain, and the phase shift in the line of sight direction is due to the terrain change by an amount of $r_2+\Delta r$ where Δr is the component of displacement parallel to the radar source

$$\phi_p \approx -\frac{4\pi}{\lambda} B \sin(\theta - \alpha) + \frac{4\pi}{\lambda}\Delta r \qquad (1)$$

The phase displacement is determined by $4\pi\Delta r/\lambda$ which is the displacement in the line of sight, and each fringe corresponds to half of the wavelength.

Thus, radar interferometry (InSAR) by extracting phase information from the interferometric image pair allows the study of surface deformation and is based on this formula:

$$\varphi_{interferometry} = \varphi_{topo} + \varphi_{defo} + \varphi_{atm} + \varphi_{noise} \qquad (2)$$

where: $\varphi_{interferometry}$: Interference phase

φ_{topo}: Topographic phase

φ_{defo}: Deformation phase

φ_{atm}: Atmospheric influence phase

φ_{noise}: Noise phase

The interference phase of the radar image pair includes the topographic phase, deformation phase, atmospheric influence phase due to signal delay when passing through the atmosphere, and other noise phases such as geometric decorrelation or baseline, temporal decorrelation, thermal noise, etc.

The deformation phase is calculated according to the formula:

$$\varphi_{defo} = \frac{4\pi\Delta r}{} \quad (3)$$

where: Δr is the deformation component in the line of sight or parallel to the slant range direction of the radar signal transmitted to the ground, λ wavelength of radar.

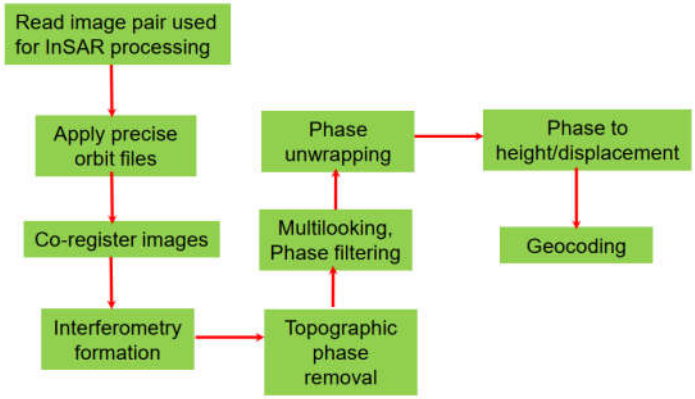


Figure 6: Processing Workflow of InSAR from Radar Images

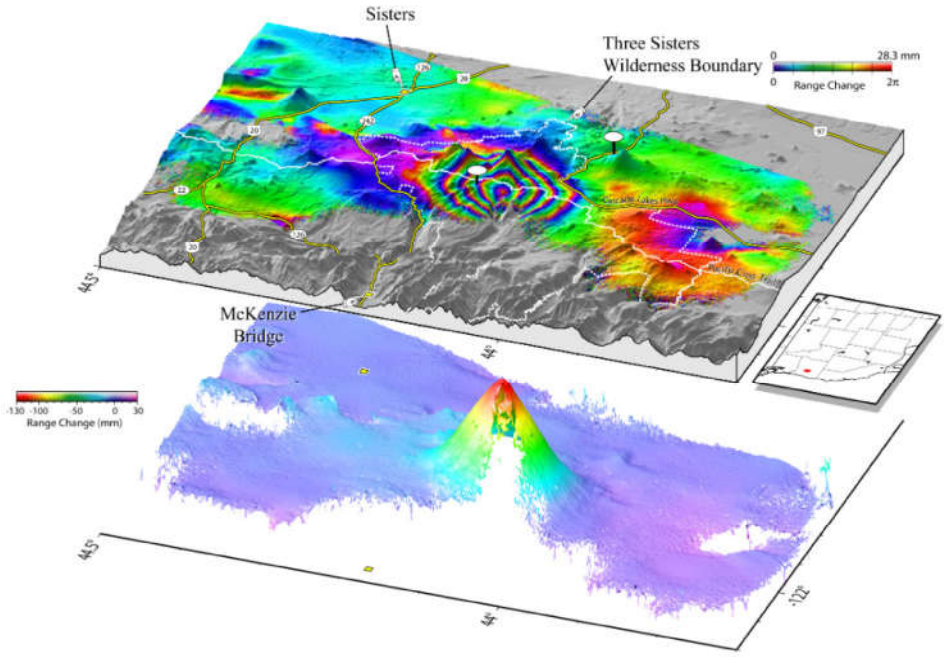


Figure 7: Interferogram image made from InSAR monitoring, showing 1995 - 2001 ground-uplift pattern centered 5 km (3 mi) West of South Sister volcano, Oregon

(Source: Public domain)

The PSInSAR (Persistent Scatterer Interferometry) method is applied for the Ninh Bình area. The processing steps of this method are carried out using SNAP and STAMPS.

The interferometric processing step using the Sentinel image set is performed on SNAP according to the following procedure (Fig. 8).

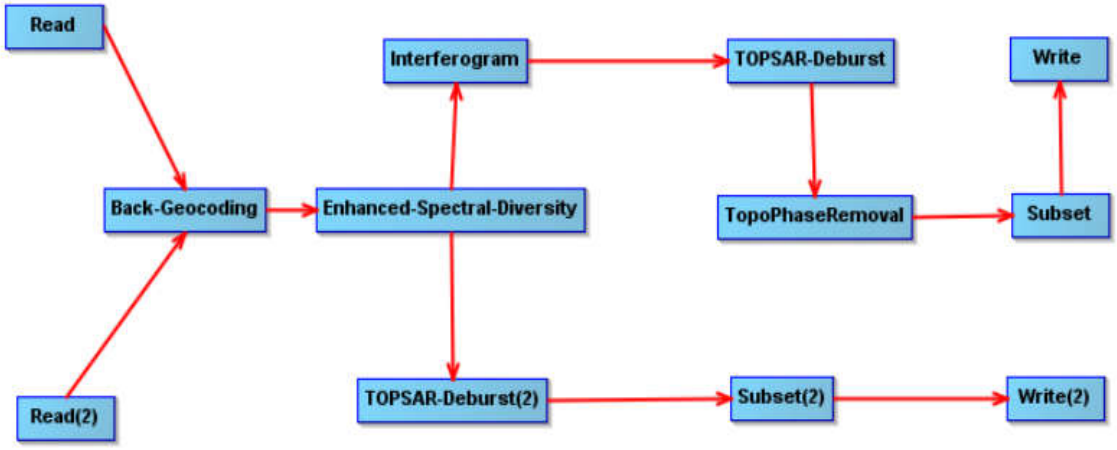


Figure 8: Interferometric Processing Workflow for Sentinel-1 Images in SNAP

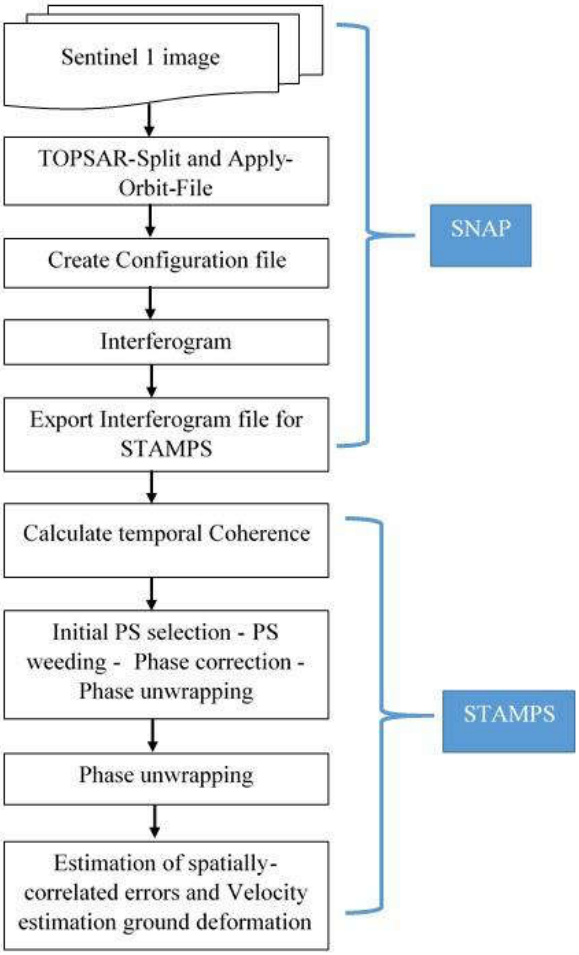


Figure 9: Diagram of image processing workflow combining SNAP and STAMPS

2.3. Material

53 photos were used from the beginning of 2020 to the end of 2021 in this study area. All image data were selected at no rainfall times.

The study area belongs to two swaths (IW2 and IW3) on Sentinel-1 images

Table 1. Collection of Sentinel-1 image data in Ninh Binh province for the period 2020 - 2021

Ord.	Date	Ord.	Date	Ord.	Date	Ord.	Date
1	09/02/2020	14	07/8/2020	27	22/01/2021	40	27/6/2021
2	21/02/2020	15	19/8/2020	28	03/02/2021	41	09/7/2021
3	16/03/2020	16	31/8/2020	29	15/02/2021	42	21/7/2021
4	28/3/2020	17	12/9/2020	30	27/02/2021	43	02/8/2021
5	09/4/2020	18	24/9/2020	31	11/03/2021	44	14/8/2021
6	21/4/2020	19	06/10/2020	32	23/3/2021	45	07/9/2021
7	03/5/2020	20	18/10/2020	33	04/4/2021	46	19/9/2021
8	15/5/2020	21	11/11/2020	34	16/4/2021	47	01/10/2021
9	08/6/2020	22	23/11/2020	35	28/4/2021	48	25/10/2021
10	20/6/2020	23	05/12/2020	36	10/5/2021	49	06/11/2021
11	02/7/2020	24	17/12/2020	37	22/5/2021	50	18/11/2021
12	14/7/2020	25	29/12/2020	38	03/6/2021	51	30/11/2021
13	26/7/2020	26	10/01/2021	39	15/6/2021	52	12/12/2021
						53	24/12/2021

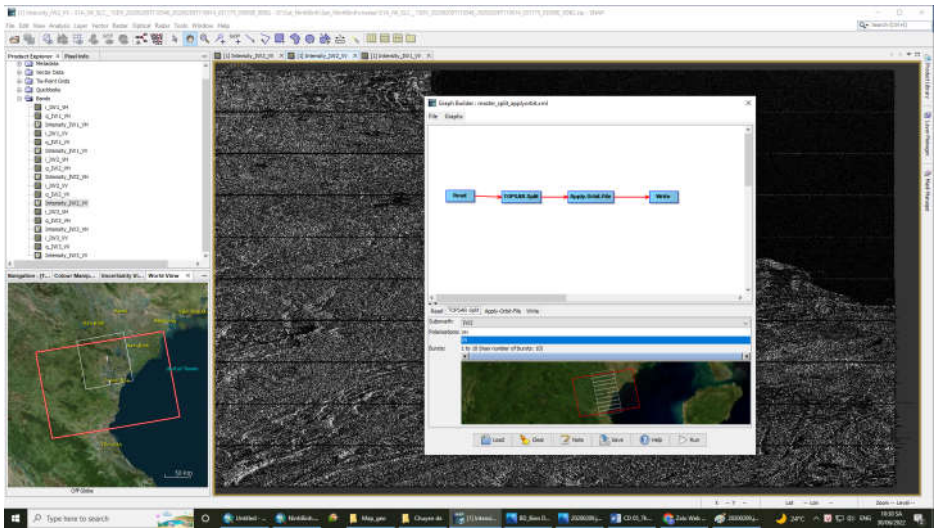


Figure 10: Registering Images of the Study Area in Ninh Binh province from Sentinel-1

3. Results and discussion

3.1. Advantages - disadvantages of InSAR

Analyzing the principles behind the creation of InSAR has demonstrated its potential application for studying land subsidence, ground cracking, both in spatial and temporal dimensions, over a wide area with millimeter-level accuracy. However, this technology also possesses both advantages and disadvantages in the processing phase.

The advantages of this technology include:

- Active satellite radar remote sensing allows for the transmission and

reception of signals, enabling the study of subsurface objects during both day and night, and being less affected by weather conditions.

- Satellite radar remote sensing helps in monitoring and researching objects in hard-to-reach areas on the Earth's surface.

- Utilizing satellite radar in studying surface deformation provides highly accurate results down to the millimeter level.

The drawbacks of this technology mainly arise from the transmission and reception of signals from subsurface objects:

- It is affected by the terrain, as well as short-range phenomena, overlapping, and shadows in radar images.

- The results of radar processing can be influenced by various sources of noise.

However, these drawbacks can be overcome during the processing phase, making this technology highly reliable for studying land subsidence, ground cracking, and achieving high-quality results.

3.2. Result of InSAR application in land subsidence in Ninh Binh

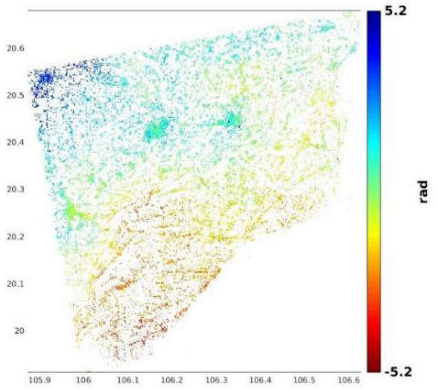


Figure 11: Results of the deformation phase of the study area after separating the topographic phase for each time point

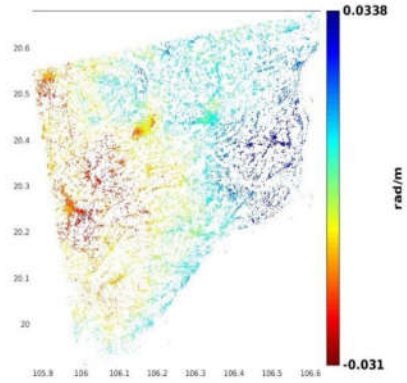
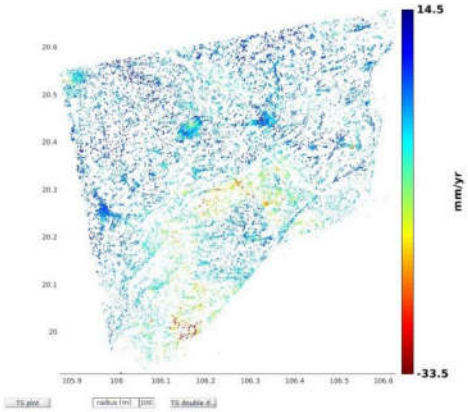
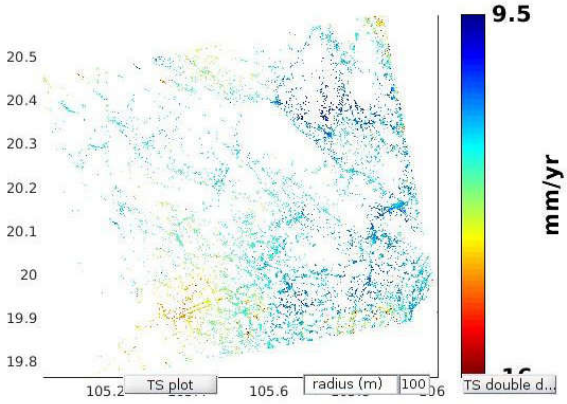


Figure 12: DEM terrain error value by satellite's orbit and angle of incidence



(a) IW3



(b) IW2

Figure 13: Topographic distortion in the center of Sentinel-1 image for the period 2015 - 2019 after removing atmospheric noise (A3)

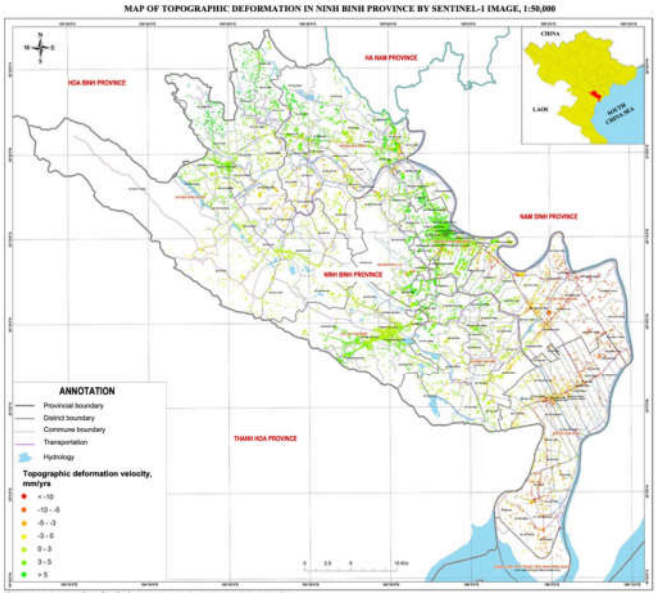


Figure 14: Results of ground deformation velocity in Ninh Binh province by Sentinel-1 image in the period of 2020 - 2021 (1:50,000)

From the results of the surface deformation map in Ninh Binh province during the period of 2020 - 2021, which includes 78,077 PS points, several areas of land subsidence have been identified. These areas include Kim Son district and Yen Khanh district, with many regions exhibiting subsidence velocities of <-10 mm/year. Some areas, such as Yen Nhan commune in Yen Mo district, Nam Binh ward, and Ninh Phong ward in Ninh Binh city, as well as the areas of certain communes located in the border region between Nho Quan district and Gia Vien district, show subsidence velocities ranging from -5 to -10 mm/year. There are also regions indicating subsidence values of 0 to -5 mm/year.

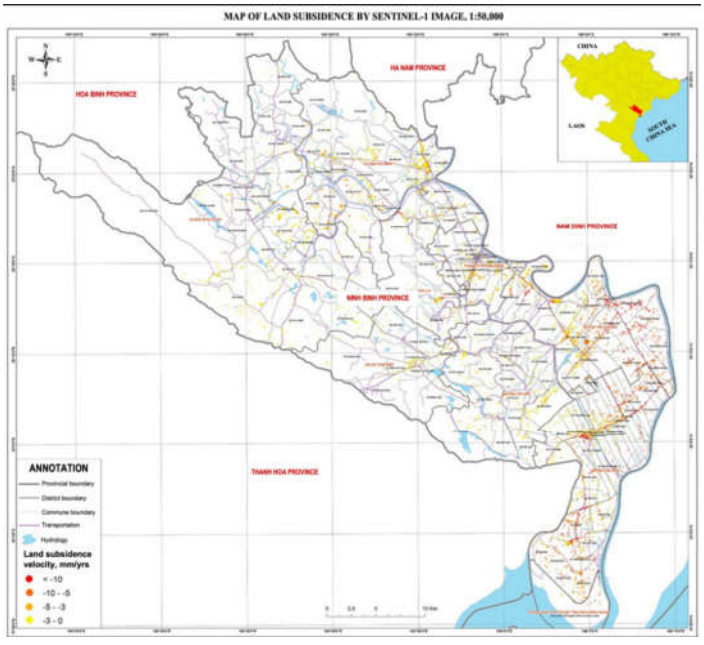


Figure 15: Results of land subsidence velocity in Ninh Binh in the period of 2020 - 2021

3.3. Discussion

InSAR results show that the points of land subsidence are concentrated in densely populated areas such as towns and cities in the province. The distribution of the subsidence points around areas undergoing urban development and transportation routes suggests that the subsidence is likely due to human-induced factors rather than natural causes.

The reality shows that from 2019 to now, there have been continuous subsidence incidents in Ninh Binh province. These subsidence incidents always occur on traffic routes and around construction areas. Specifically, in February 2019, a section of the road more than 60 m long in Thon 1, Kenh Ga**,** Gia Thinh commune, Gia Vien district sank into the river, houses were cracked, gates and yards were eroded [10]. In November 2020, the houses of the households in Kim Dai village, Kim Chinh commune, Kim Son district, next to Vac River, next to the construction site of the Kim Dai wharf project suffered foundation subsidence, and the wall was cracked [11]. In December 2021, a sinkhole appeared on provincial road 477 (ĐT477) through Gia Phuong commune, Gia Vien district [12]. In July 2022, the area of Ngo Quyen temple, Hamlet 6, Khanh Trung commune, Yen Khanh district was cracked and subsided during the construction of the traffic route connecting Khanh Trung commune and Khanh Cong commune (Yen Khanh district) [13]. In February 2023, many subsidence points appeared on the Cau Gie - Ninh Binh highway, especially the area adjacent to the highway surface and the civilian underpass bridge [14]. In September 2023, the construction area of the Kim Doi irrigation pump station project and level 1 irrigation system, Gia Lam commune, Nho Quan district suffered subsidence, and the canal bank leading to the suction tank of the pump station was broken [15].

The above research results of ground subsidence using radar interferometry need to be verified experimentally. The research results from project code VT-UD.05/18-20 have been confirmed in land subsidence studies in the Cam Pha - Quang Ninh area. As a result of Radar interference analysis, it was found that the subsidence area in the Cam Pha city center is concentrated in the two districts of Cam Dong and Cam Son districts, and extends beyond the study area to Cua Ong and Mong Duong districts (Fig. 16) [16]. The average subsidence rate is -3 to -5 mm/year. The sinkholes in the Cam Tay area, Cam Pha were recorded on October 6, 2018. The value chain processed from Sentinel-1 image data shows the time when abnormal fluctuations occurred before the sinkhole appeared for a long time. Figure 17 shows the data series recording abnormal fluctuations starting from June 2, 2018. The strong subsidence phenomenon started to occur on September 18, 2018.

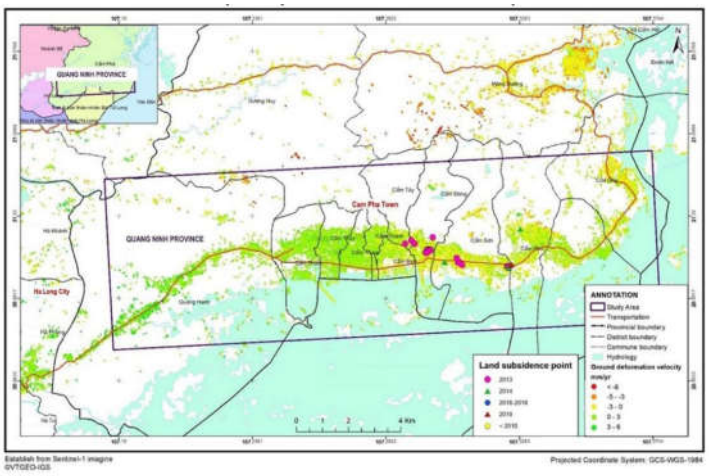


Figure 16: Integrated land subsidence statistics on terrain surface deformation data in Cam Pha - Quang Ninh

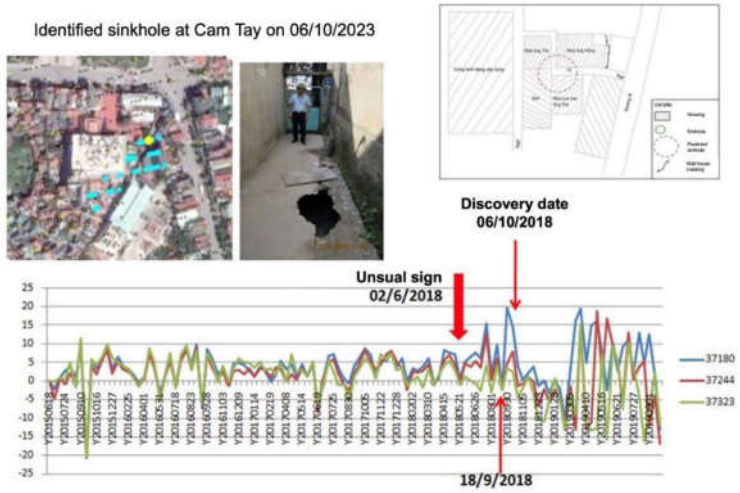


Figure 17: Time series data of Land subsidence in Cam Tay - Cam Pha - Quang Ninh by InSAR method

Thus, the results of radar interference analysis show reliability with the ability to anticipate abnormal signs that can lead to actual sinkhole phenomena.

To accurately determine the cause of the subsidence in the research area, it is necessary to employ various types of research. From there, appropriate solutions can be proposed to prevent and mitigate damages in Ninh Binh province.

4. Conclusion

Through the method of satellite interferometry, we can establish surface deformation maps for different areas. The results of the surface deformation maps allow us to determine and assess the current status of areas experiencing land subsidence and ground cracking within the research area.

The construction of the surface deformation maps using the radar interferometry method in this study is performed through two platforms. The input data processing for the image dataset, the interferometric processing on the Snap platform using the Python language, and

the processing of the unwrapping phase, noise removal, and elimination of low correlation points on Stamps are carried out on the Linux operating system.

Field studies show that the application of radar interference methods to study terrain surface deformation *(*specifically subsidence) with millimeter accuracy shows reliability with the ability to anticipate abnormal signs that can lead to actual phenomena.

In this study, using radar interferometric processing for a dataset of 53 Sentinel-1 images from 2020 to 2021 in Ninh Binh province, a total of 77,087 Persistent Scatterer (PS) points were obtained. The maximum subsidence value is found to be less than -10mm/year in the Kim Son and Yen Khanh districts.

The initial causes of the observed subsidence can be attributed to human activities in the province. Therefore, to accurately determine the underlying causes of the subsidence in the research area, it is necessary to combine multiple geological methods. This will help in identifying the specific factors contributing to the subsidence. By doing so, appropriate solutions can be proposed to mitigate and minimize the damages in Ninh Binh province.

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