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Proposed Method for Improving PSI Capabilities in Ground Deformation Monitoring for The Application of Geo-Energy Projects

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Abstract

Persistent Scatterer Interferometry (PSI) is a powerful Synthetic Aperture Radar (SAR) technique capable of detecting millimeter-scale deformation. However, the technique faces limitations related to the observed ground or areas and the phase unwrapping stage. This research proposes an integrated approach to address these limitations by combining multiple images from different sensors. The integrated method aims to provide more coverage and additional data to partially overcome the weaknesses of the PSI technique. The article introduces the proposed integrated approach and provides insights into the workflows required to apply this method on geo-energy projects.

1. Introduction

1.1 Background

The technology of Synthetic Aperture Radar has brought us a powerful remote monitoring method that can keep going constantly without the worry of weather or daylight time. SAR monitoring can work 24 hours for 7 days non-stop, with revisiting time that depends on the SAR sensor. This makes the technology very useful when it comes to environmental monitoring. This technology has been applied in multiple fields with different purposes such as studying icebergs, agricultural monitoring, tracking oil spills, and mapping.

One of the technique that is built on SAR is Persistent Scatterer Interferometry (Ferretti et al., 2001). Persistent Scatterer Interferometry (PSI) technique remains a powerful remote sensing method in terms of ground deformation monitoring. PSI utilizes a series of radar images taken from satellites to detect and measure very small ground movements over time. However, despite being powerful, PSI can still encounters multiple obstacles. Some of the major obstacles is the monitoring of heavily vegetated area, snow covered area, rapid urban development, and other low reflectivity areas.

Geo-energy is an emerging topic in response to global demand of sustainable and efficient energy solutions. Geoenergy often implies injecting (and/or extracting) fluids into (from) the subsurface, which involves coupled thermo-hydro-mechanical-chemical (THMC) processes. Geo-energy is a multi-disciplinary project that requires the attention of many expertises and this includes expertise in deformation. The monitoring is a crucial supporting component to ensure the smooth progress of geo-energy development. This technique is particularly valuable in geo-energy projects, where understanding subtle changes in the Earth's surface can indicate important subsurface processes and structural integrity issues.

Traditional PSI methods typically rely on images from a single sensor, which can limit the spatial and temporal resolution of the data. The proposed multi-sensor approach has the potential to significantly enhance the accuracy and reliability of PSI by providing more comprehensive and frequent data coverage.

In this context, we propose a novel method that combines images from multiple sensors to improve the PSI technique's capabilities for ground deformation monitoring. While this method has broad applications, our focus is on its implementation in geo-energy projects. By integrating data from various sensors, we aim to achieve a more detailed and continuous understanding of ground movements, thereby enhancing the safety and efficiency of geo-energy operations. The proposed multi-sensor PSI method focuses on the strengths of different satellite platforms, each with unique imaging characteristics. Combining these diverse datasets can overcome the limitations of single-sensor PSI, offering a more robust and resilient monitoring system. This integrated approach is expected to provide better spatial coverage, higher temporal frequency, and improved accuracy in detecting ground deformation.

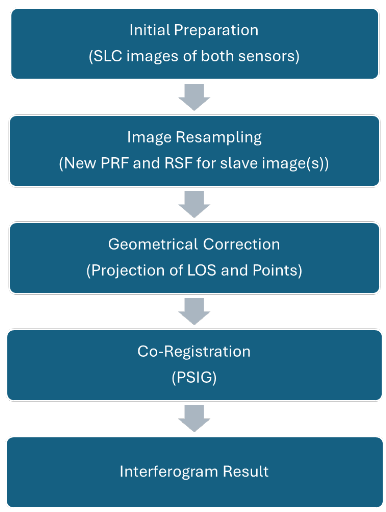

Figure 1. Coarse workflow of the initial steps on tackling the multi-sensor image fusion.

In the following sections, we outline the current state of the art in both PSI and geo-energy projects, highlighting the technological advancements and practical applications that set the stage for this proposed method. We also discuss the potential benefits and challenges associated with integrating multi-sensor images for PSI and present our methodology for achieving this integration.

1.2 State of the art

Geo-energy projects , encompassing geothermal energy, carbon sequestration, and enhanced oil recovery, represent a major position in the quest for sustainable energy solutions. Geo-energy has the potential to reduce emissions up to 25% of the total emissions in the atmosphere. These projects demand precise monitoring and management to ensure efficiency and safety. Innovations in remote sensing and geospatial technologies will benefit greatly geo-energy projects, with PSI emerging as a crucial tool.

PSI stands at the forefront of remote sensing techniques, offering high-resolution, accurate measurements of ground deformation over time. By utilizing radar images acquired from satellites, PSI can detect and monitor minute displacements of the Earth's surface, which are essential for assessing the stability and integrity of geo-energy infrastructure. The application of PSI in geo-energy projects enables detailed analysis of subsurface activities, contributing to enhanced safety protocols and optimized resource extraction.

In the following sections, we delve deeper into the state of the art for both PSI and geo-energy projects. This exploration will highlight the latest technological advancements, practical applications, and the synergistic integration of PSI in monitoring and improving the efficiency of geo-energy endeavours.

1.2.1 Persistent Scatterer Interferometry

Persistent Scatterer Interferometry technique was first proposed by (Ferretti et al., 2001) as an advanced remote sensing technique designed to exploit multiple Synthetic Aperture Radar (SAR) images acquired over time by SAR sensors. PSI is a branch of SAR technology that focuses on identifying and analyzing Persistent Scatterers (PS), which are stable points on the ground that consistently reflect radar signals back to the sensor. This technique is meant to exploit at least two complex images that are gathered by sensors taken on different times over the same area to generate an interferometric pair, allowing for the measurement of ground deformation with high precision.

The repeated acquisition of images over a given area is usually performed with the same sensor or sensors with identical system characteristics (Crosetto et al., 2016). This consistent monitoring is crucial for detecting and analysing minute ground displacements over time. The repeated observations enable the differentiation of true ground movements from atmospheric and orbital artifacts, thereby enhancing the accuracy and reliability of deformation measurements.

Despite its significant advantages, PSI is not without challenges. Issues that affect the accuracy and robustness of PSI results are related to data availability and the presence of sufficient Persistent Scatterers (PS). Factors such as snow cover, dense vegetation, and extensive constructions can limit the availability of PS, thereby impacting the quality of the deformation measurements. Additionally, PSI is not ideally suited for measuring rapid ground movements.

By combining images from different SAR missions, such as the European Space Agency's Sentinel-1, TerraSAR-X, and COSMO-SkyMed, researchers can improve the temporal resolution and spatial coverage of PSI-derived measurements. This multi-sensor approach enhances the robustness of the monitoring system, providing more frequent and detailed observations of ground deformation. The continuous development of multi-sensor integration techniques will enhance the capabilities of PSI, making it an even more powerful tool for projects that involve ground deformation monitoring.

1.2.2 Multi-Sensor Image Fusion

The multi-sensor fusion approach in Persistent Scatterer Interferometry (PSI) holds great promise for improving the accuracy and reliability of ground deformation monitoring. By combining data from multiple SAR sensors with varying system characteristics, it is possible to overcome some of the limitations inherent in single-sensor PSI techniques, such as temporal gaps in data acquisition and limited spatial coverage.

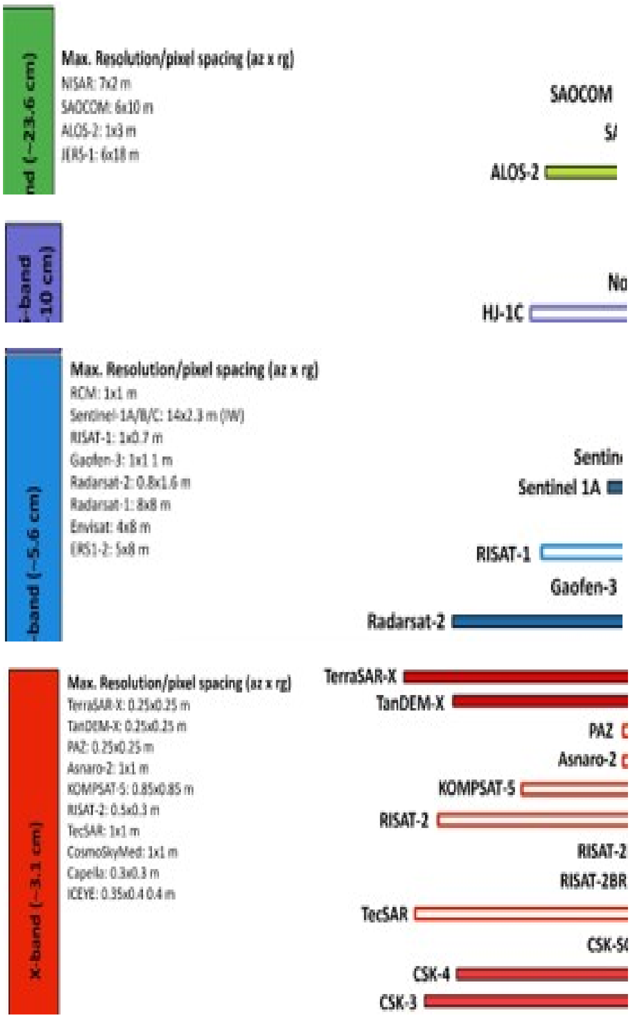

Figure 2. SAR satellite missions.

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However, despite its potential, the theoretical framework for multi-sensor fusion is still underdeveloped, presenting challenges that require to be studied. One of the primary challenges is the heterogeneity of the data This heterogeneity can complicate the process of data fusion, as it requires sophisticated algorithms to align and integrate the diverse datasets. Theoretical models that can effectively handle these differences and ensure the seamless integration of multi-sensor data are still lacking. To give an idea of the heterogeneity of the sensors, below a table featuring each sensors properties is presented.

Name	Mean Altitude (km)	Inclination	Repeat Cycle (days)	Band	Resolution (Rng x Azi [m])
Sentinel-1	693	98.19°	12	C (5.4 Ghz)	20 x 5
TerraSAR-X	514	94.85°	11	X (9.65 GhHz)	3 x 3
COSMO-SKYMED	620	97.8°	16	X (9.6 GHz)	3 x 3
SAOCOM	620	97.89°	16	L (1.275 GHz)	10 x 10 - 100 x 100
PAZ	514	97.44°	11	X (9.65 GHz)	1 x 1 - 6 x 18
NISAR	747	98.4°	12	S (3.2 GHz) and L (1.25 GHz)	4-24 (S-band), 10 (L-band)

Table 1. Summary of the properties of each current active sensors and potential material for the fusion.

To address the theoretical gaps, further research is needed in some of the key areas. However, this study will mainly focus on the data alignment and integration. The goal is to develop an algorithm to align and integrate heterogeneous SAR datasets, considering differences in frequency, resolution, and imaging geometry.

2. Study area

The current experimental stage of this method will be applied on a mine. Mines are selected because of the potential of ground instability that can be detected by PSI. The chosen location of the trial is the Quellaveco and Toquepala mines of Peru.

The Toquepala deposit is a large copper-molybdenum porphyry deposit, extending over an area of 3.3 by 3.5 km. The Toquepala mine was opened by Southern Peru Copper Corporation in 1960. Now, the mine is operated by Southern Copper Corporation, subsidiary of Grupo Mexico. As of 2009, Toquepala reported about 13 million tons of contained copper metal in proven and probable ore reserves, at an average grade of 0.47% Cu. The mine is currently expanding its concentrator capacity to increase annual copper production by 100,000 tonnes

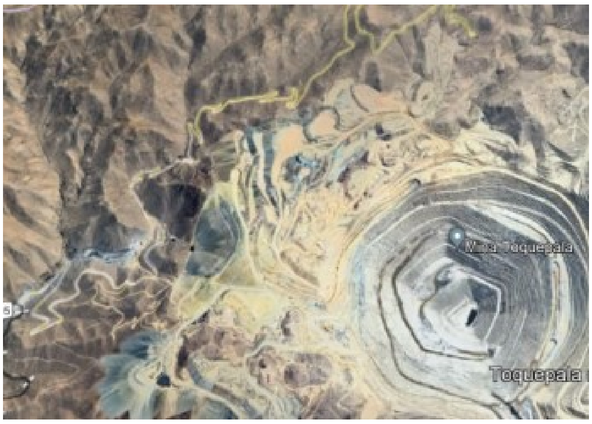

Figure 3. Google Earth view of Toquepala mine

The Quellaveco deposit is located about 15 km north of Toquepala. It is a large porphyry copper-molybdenum system centered on an early Eocene multiphase quartz monzonite porphyry stock emplaced into an older granodiorite pluton. As of 2015, Quellaveco had JORC compliant ore reserves of 1.332 Gt @ 0.58% Cu, 0.019% Mo, plus measured and indicated resources of 776.1 Mt @ 0.38% Cu, 0.013% Mo.

Figure 4. Google Earth view of Quellaveco mine

Both deposits are part of the Paleocene to early Eocene porphyry copper belt of the central Andes. Supergene enrichment has played an important role in the formation of the copper mineralization at Toquepala and Quellaveco. The deposit is located in a region with a long history of mining and are well-served by infrastructure including roads, railways, ports and smelting facilities

The Toquepala and Quellaveco mines are some of the most significant copper deposits in Peru, with substantial remaining resources and potential for further discoveries in the surrounding area. Their proximity to each other and to established mining infrastructure make them an ideal study area for understanding the regional geology and mineralization.

The Toquepala and Quellaveco mines provide an ideal study area to apply the PSI technique due to the significant mineral resources, favourable logistics, potential for ground instability, regional geological context, and availability of relevant remote sensing data.

Future prospects and plans will be on applying this technique into geo-energy projects, mainly geothermal and carbon capture and storage.

3. Methodology

3.1 Pre-Processing Preparations

Images that will be used during this experimental stage will be obtained by Sentinel-1 and TerraSAR-X. Image that is obtained from Sentinel-1 will be assigned the role of super-master, while image from TerraSAR-X will be assigned as the sub-images to be co-registered to the Sentinel-1.

Sentinel-1 is the first constellation of the Copernicus Programme that is conducted by the European Space Agency (ESA). Initially, the mission was composed of two satellites, which is Sentinel-1A, launched on 3 April 2014 and Sentinel-1B, launched on 25 April 2016 but then there are two more satellites in development, Sentinel-1C and Sentinel-1D. On December 2021, Sentinel-1B was retired due to a power supply issue. Sentinel-1C is planned to launch around the final quarter of 2024. Because of the policies of ESA and European Commission, Sentinel-1 data is easily accessible and free to use for public, scientific, and commercial purposes. The main operational mode to be used in this case is the Interferometric Wide Swath (IWS) mode.

TerraSAR-X is a constellation launched jointly by German Aerospace Center (DLR) and EADS Astrium. The constellation was launched on 15 June 2007. TerraSAR-X offers multiple modes such as SpotLight, StripMap, and ScanSAR. For ease of use, the mode that will be used in this case is the StripMap mode.

3.2 Image Resampling

SAR data needs to be resampled to create a regularly-spaced image. There are many ways to resample SAR data, but it needs to be kept in mind as using the ¨wrong¨ resampling method can cause doppler effect and more noise on the resulted images.

Resampling step to be able to conduct the proposed method. To put it simply, the sub-images need to be resampled to match the properties of the super-master image to ensure a successful co-registration. Co-registration itself is a step where all the slave-images are aligned and corrected toward the super-master image. The goal is to have the same pixel of different images to have the same footprint. A not precise co-registration can cause a coherence reduction of the interferogram and producing accentuated linear terms.

In this case, an image from TerraSAR-X is chosen to be applied to the Sentinel-1 image acting as the super-master. The resampling requires knowing the RSF (Range Sampling Frequency) and the PRF (Pulse Repetition Frequency) of the super-master image. The input format should be in real or complex images, in this case the input will be SLC (Single Look Complex) images.

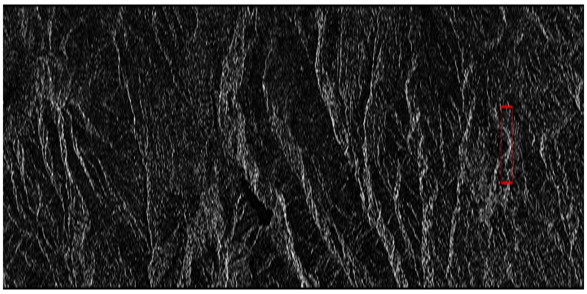

Figure 5. The SM Sentinel-1 complex image

The first resampling method is by enlarging the input dimensions into the output dimensions. The process utilizes a two dimensional direct Fast Fourier Transform (FFT) to pass in the frequency domain. Then by enlarging the spectrum by means of a zero fill (with a special care for complex images in the determination of the location of the zeros in the column i.e. azimuth direction, due to the presence of a non-zero centred spectrum) and finally by a two dimensional inverse FFT (having the size of the output image) to return to the spatial domain and give the over-sampled image.

The over-sampling algorithm is based on the increase of the sampling rate of a band limited, sampled input signal through use of the frequency domain. A discrete time signal can be over-sampled simply taking its spectrum, adding zeroes at the spectrum tails and returning to the time domain with a larger number of samples. Although it is simple, this method need to be handled with care, mainly for the mapping introduced by the Discrete Fourier Transform used for going between the time and the frequency domains and for the presence of the Doppler Centroid frequency in the azimuth (column) direction. The major modification of the algorithm is related to the presence of a non zero centred spectrum in the azimuth direction while the range direction can be treated in the same way as explained for the real image (in other words the original range spectrum is zero centered).

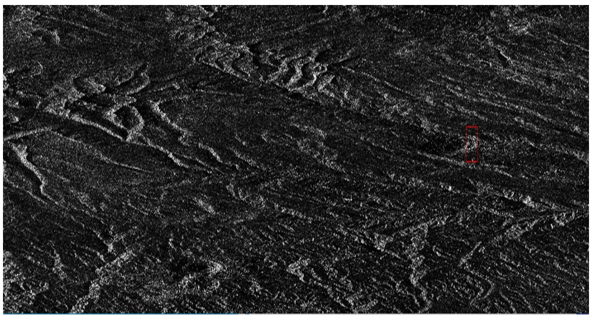

Figure 6. A resampled TerraSAR-X complex image into the Sentinel-1 properties with new resolution.

3.3 Geometric Issues

The integration of data from multiple sensors introduces several geometric challenges that must be addressed to ensure the accuracy and reliability of the final interferogram. One of the primary concerns is the accurate co-registration of the sensor data, as any misalignment can lead to phase incoherence and errors in the unwrapped phase.

Additionally, each sensor has its own unique geometric distortions, such as radial or non-linear distortions, which need to be corrected to maintain spatial alignment across the multi-sensor dataset. Another critical issue is the handling of sensor-specific phase noise characteristics and phase discontinuities that can arise due to differences in imaging geometry, radar wavelength, and other factors.

Projecting the LOS is the first idea to solve the geometric issues. This idea can be described as how will the range on Sentinel-1 will be seen from the sensor of TerraSAR-X. Currently, to tackle the geometric issues of sensors, basic concepts of geometry are used, accompanied by properties provided by each sensors' provider. Addressing these geometric challenges through advanced data fusion and integration techniques is crucial to generating a coherent and accurate interferogram that leverages the strengths of the multi-sensor approach

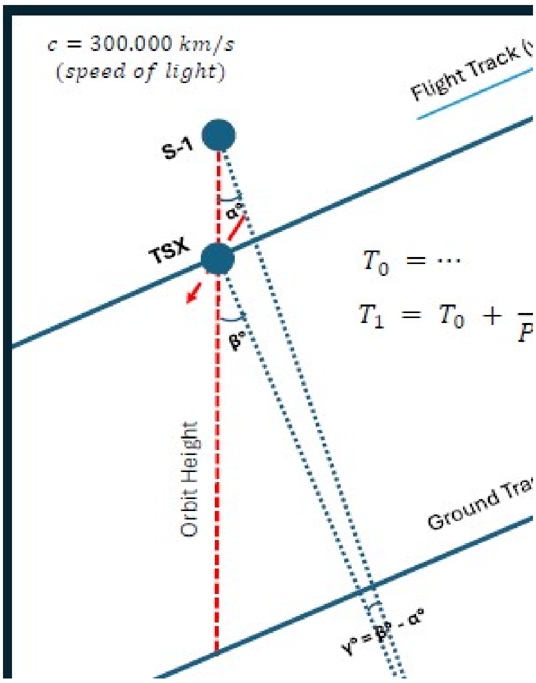

Figure 8. A sketch on how to start tackling the geometrical issue.

3.4 Interferogram generation

The key step in the PSI processing workflow is the generation of the final interferogram. This involves several crucial steps. Persistent scatterers are identified from the stack of coregistered SAR images. The selection of PS points is typically based on specific criteria, such as a minimum coherence threshold and amplitude dispersion index. Once the PS points are identified, the phase information from the interferometric pairs is unwrapped to obtain the absolute displacement values.

This phase unwrapping process is critical, as it removes the 2π ambiguity inherent in the wrapped phase measurements. The unwrapped phase values are then converted to displacement estimates by applying the appropriate conversion factor based on the radar wavelength and the imaging geometry. Combining multiple sensors can provide an improvement into the phase unwrapping stage because of the differing information of each sensor than can help solve the ambiguities. By considering the strengths and weaknesses of each sensor, fusion techniques can determine the most reliable unwrapped phase values.

The images are processed through the PSI chain of the Geomatics (PSIG) Division of CTTC (Devanthéry et al., 2014). The first generation made was to test the feasibility of the resampling method. In this case, the resampled images of TerraSAR-X were run through the process to achieve the interferograms.

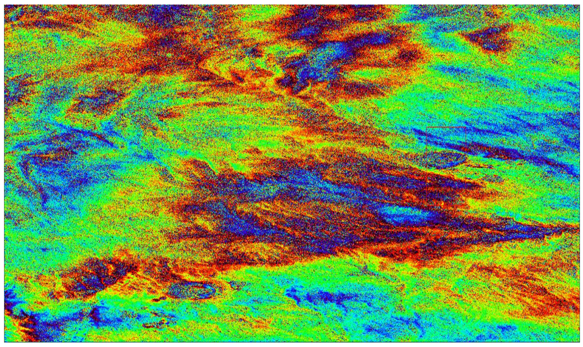

Figure 9. Interferogram of the resampled TerraSAR-X image to the properties (PRF and RSF) of Sentinel-1

4. Conclusion

The multi-sensor fusion can be a promising technique to overcome the problem related to PSI technique. By combining data from multiple SAR sensors, it is possible to enhance the spatial and temporal resolution of ground deformation measurements, thereby improving the robustness and reliability of the monitoring system.

Nevertheless, the theoretical framework for multi-sensor fusion in PSI is still underdeveloped, with several key challenges related to data heterogeneity, temporal alignment, phase unwrapping, and error propagation. Addressing these theoretical gaps is essential to realize the full potential of multi-sensor fusion in PSI. Future research should focus on the other potential key issues such as temporal interpolation and the error propagation model.

A successful implementation could improve the field of ground deformation monitoring, offering critical insights for a wide range of geospatial and environmental applications. Thus will lead to better monitoring and management ground monitoring related projects, ensuring their safety, efficiency, and awareness. Through continued research and collaboration, we can unlock the full potential of this innovative approach, driving progress towards a more sustainable and resilient future.

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