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Extracting 3-dimensional co-seismic displacement using InSAR techniques

Dmitry Sidorov-Biryukov, Dragana Đurić
University of Belgrade, Faculty of mining and geology

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Introduction and problem analysis

Synthetic-aperture radar (SAR) has transformed geophysics, providing invaluable insights into Earth's dynamics and structure. Initially developed for military purposes, SAR technology played a pivotal role in formulating plate tectonics theory, a cornerstone of modern geosciences. One noteworthy SAR mission, Sentinel-1, launched in 2014 [1], employs C-band radar aboard satellites Sentinel-1A and Sentinel-1B, orbiting Earth. This constellation enables frequent revisits to the same region every 14 days, enhancing comprehensive monitoring. Sentinel-1 data's open accessibility enhances its utility for scientific research, particularly for applications like differential interferometry (DInSAR), crucial for monitoring fault zones, surface ruptures, and infrastructure damage.

This research aims to utilize Sentinel-1 data to analyze post-crisis earth movements, such as those following major earthquakes or volcanic eruptions, to deepen our understanding of the underlying physics. Despite challenges such as instrumentation limitations and weather constraints, Sentinel-1 imagery offers a reliable data source, supplementing traditional geophysical methods. While various studies have documented ground deformations following earthquakes, this research seeks to unify methodologies and propose a standardized algorithm for extracting three-dimensional displacement maps from ascending and descending Sentinel-1 images [2].

Materials and methods

The Sentinel-1 mission provides data products categorized from level 0 to level 2 [3]. For InSAR research, a commonly used data product is a level-1 Single Look Complex (SLC) from the Interferometric Wide (IW) swath mode, with a spatial resolution of 5x20 meters [4]. This research focuses on outlining the standard processing chain for SAR images to facilitate subsequent unwrapping, rather than delving into image preparation and phase unwrapping.

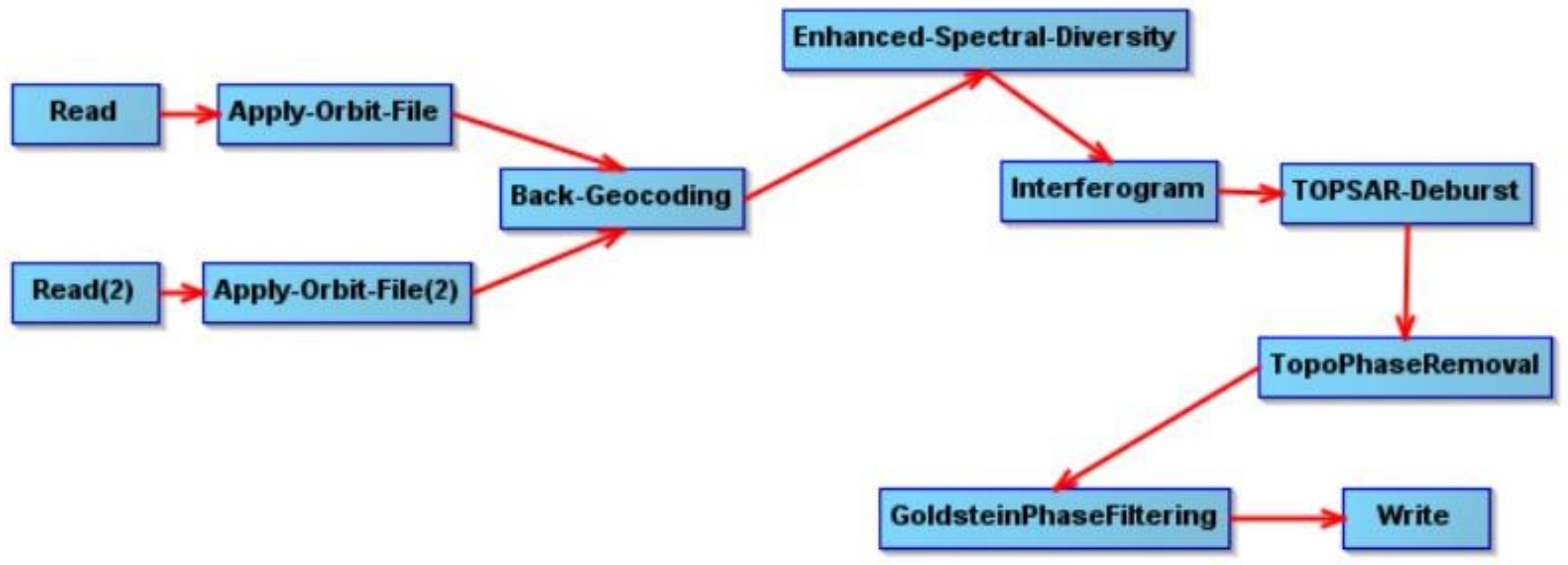
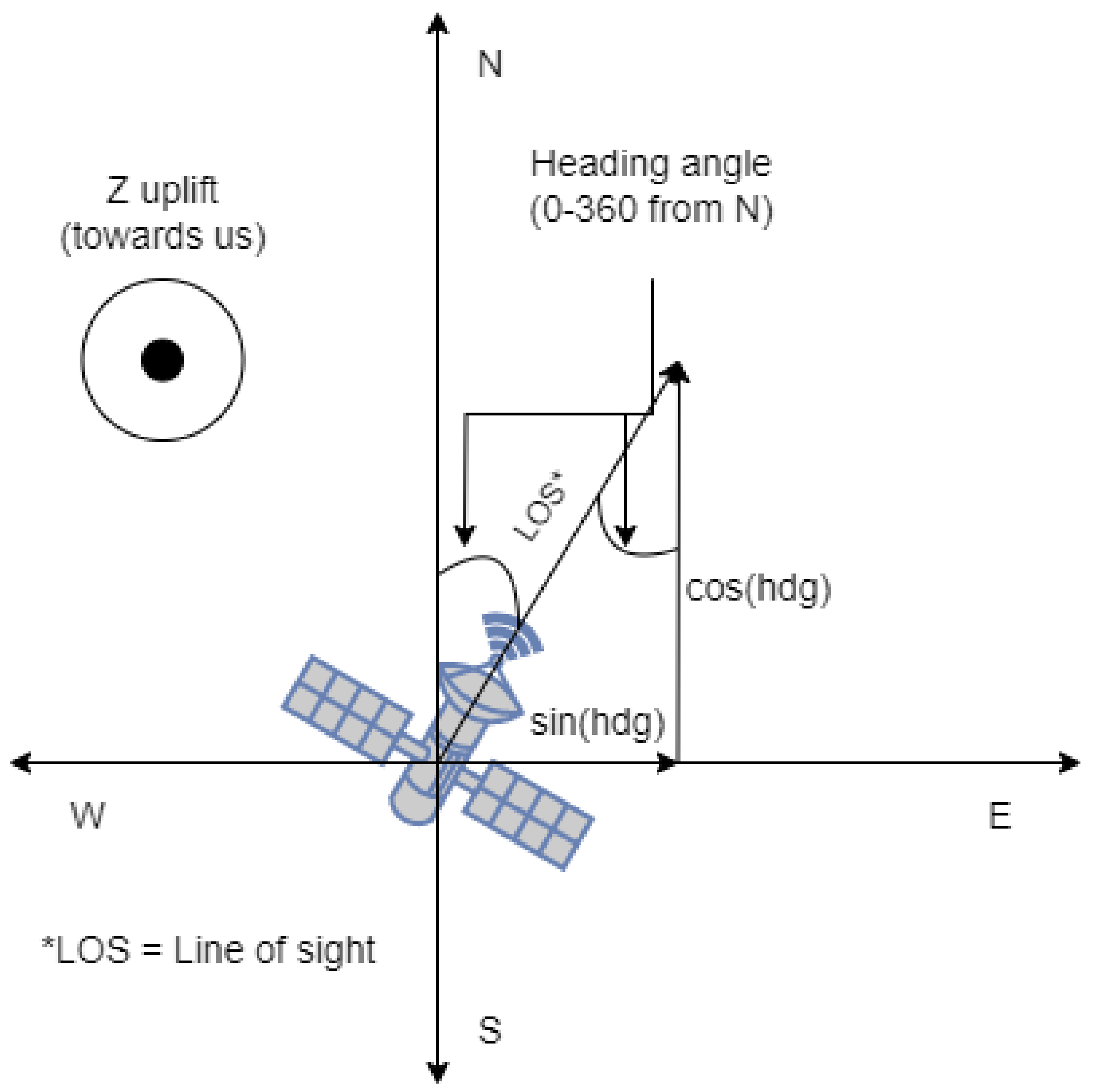


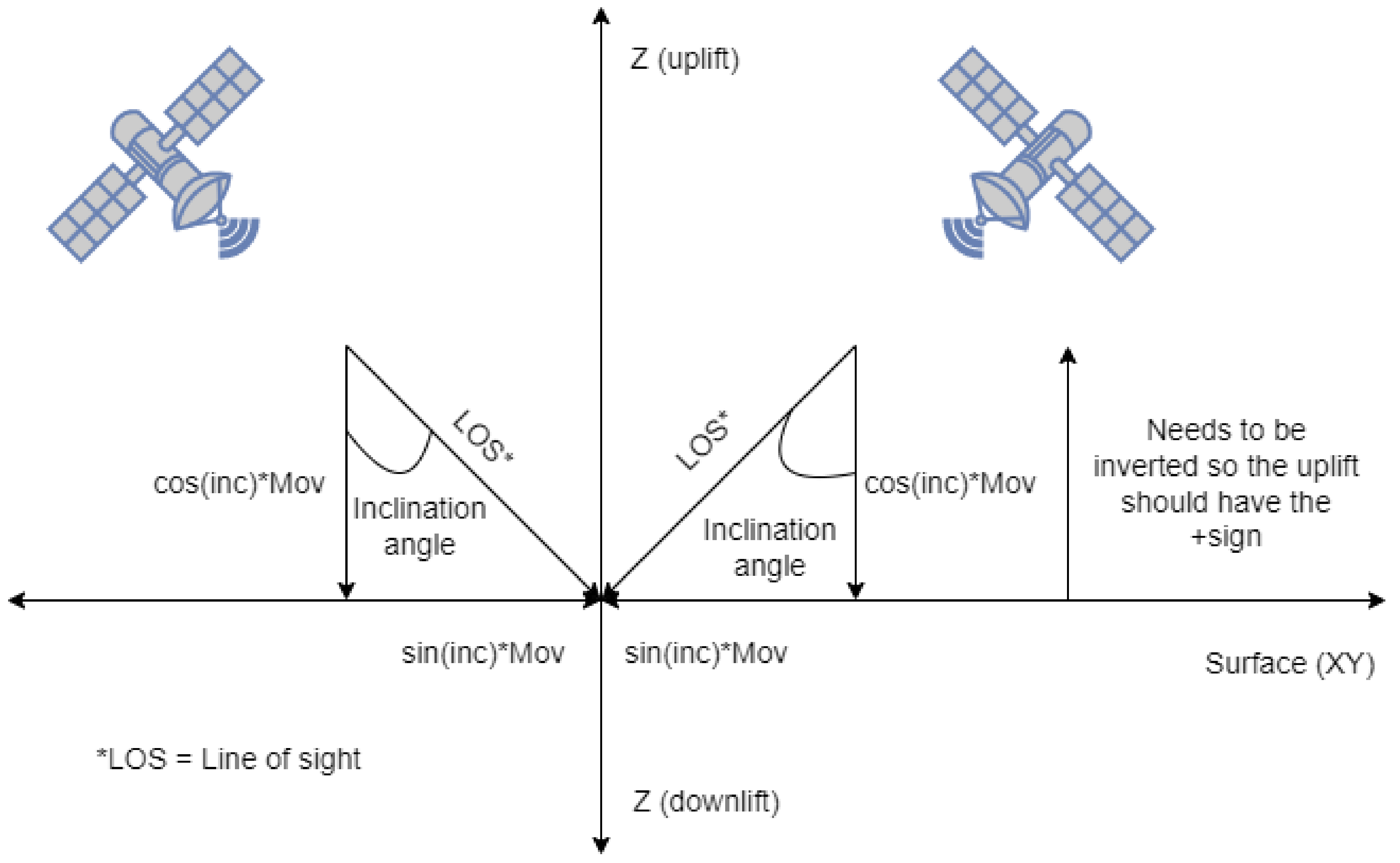
Figure 1. Diagram of the standard DInSAR data processing

Phase unwrapping, essential for deriving the displacement image along the satellite's Line of Sight (LOS), was conducted using SNAPHU [5]. However, the intricacies of this process are beyond this study's scope. Once LOS displacement data are obtained, they can be utilized for initial interpretations. However, combining both ascending and descending images of the same area enables the extraction of three-dimensional surface movements.
A formula presented in previous research [6] regarding the relationship between acquisition geometry (incidence angle and satellite track heading angle) and LOS measurements yields questionable results and lacks information regarding the extraction of movement in the N-S directions.
This study suggests leveraging the availability of two independent images (ascending and descending) for nearly all areas of interest globally, courtesy of Sentinel-1. Employing simple geometry, this method facilitates ground movement estimation, as depicted in accompanying figures 2 and 3. This approach enables rapid ground movement assessment following seismic or volcanic events, thanks to the swift availability of satellite data, contingent on satellite orbit.
However, there are notable drawbacks to this method. Precision is compromised due to the unique inclination angle of each pixel and the horizontal subswaths. To mitigate this, separate processing is necessary to align subswaths between images. Additionally, phase unwrapping is a delicate process, leading to results that are more qualitative than quantitative. Nevertheless, the latter can be considered depending on the specific task and the availability of field data.



*LOS = Line of sight

Figure 2. Diagram of the satellite orientation: Top-down view



*LOS = Line of sight

Figure 3. Diagram of the satellite orientation: Cross-sectional view

Test Case Insights

To illustrate the proposed method, we analyze the seismic event of magnitude 6.9 that occurred in Indonesia on August 5, 2018, at 11:46:38 (UTC). According to the United States Geological Survey (USGS), the earthquake took place as a result of shallow thrust faulting near the Flores Back Arc Thrust. Preliminary focal mechanisms suggest slip occurred either on a shallow, south-dipping thrust fault, or on a steep, north-dipping reverse fault. The seismic activity aligns with the convergence of the Sunda and Australia plates at approximately 70 mm/yr in a north-south direction[7].

For the DInSAR experiments, two ascending and two descending SAR images were collected and processed according to standard procedures detailed in the previous chapter. The ascending images were dated August 2, 2018, and August 8, 2018, while the descending images were dated July 25, 2018, and August 6, 2018.

All images were acquired through the Copernicus hub [8], with both polarizations available; however, utilizing identical polarizations for both transmission and reception is considered best practice for processing.

The resulting data comprises two bands representing displacement in the Line of Sight (LOS) of the ascending and descending SAR images. Using the prescribed idea, we derived the true vertical and horizontal movements. Notably, the displacement vectors converge towards the epicenter, reflecting the event mechanism. Given the earthquake's location near the Flores thrust, the surface responds by leaning towards the subduction zone at the epicenter. Analysis of vertical movement reveals minimal uplift around the epicenter, while the western region experiences an uplift of approximately 0.5 meters. This observation aligns with the event mechanism, where the subduction zone remains stationary while the western area undergoes uplift.

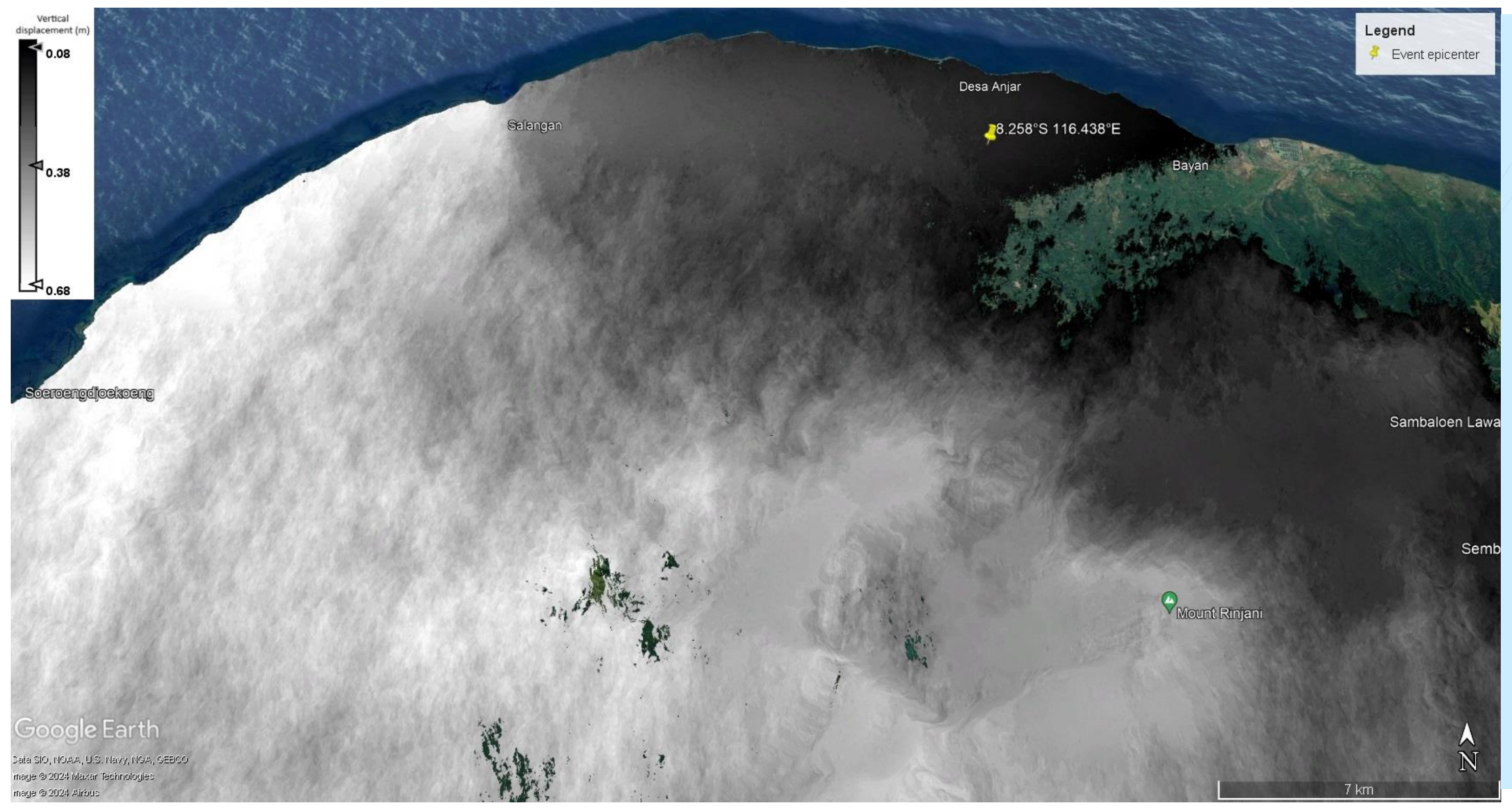


Figure 4. Result of the calculation for the vertical component

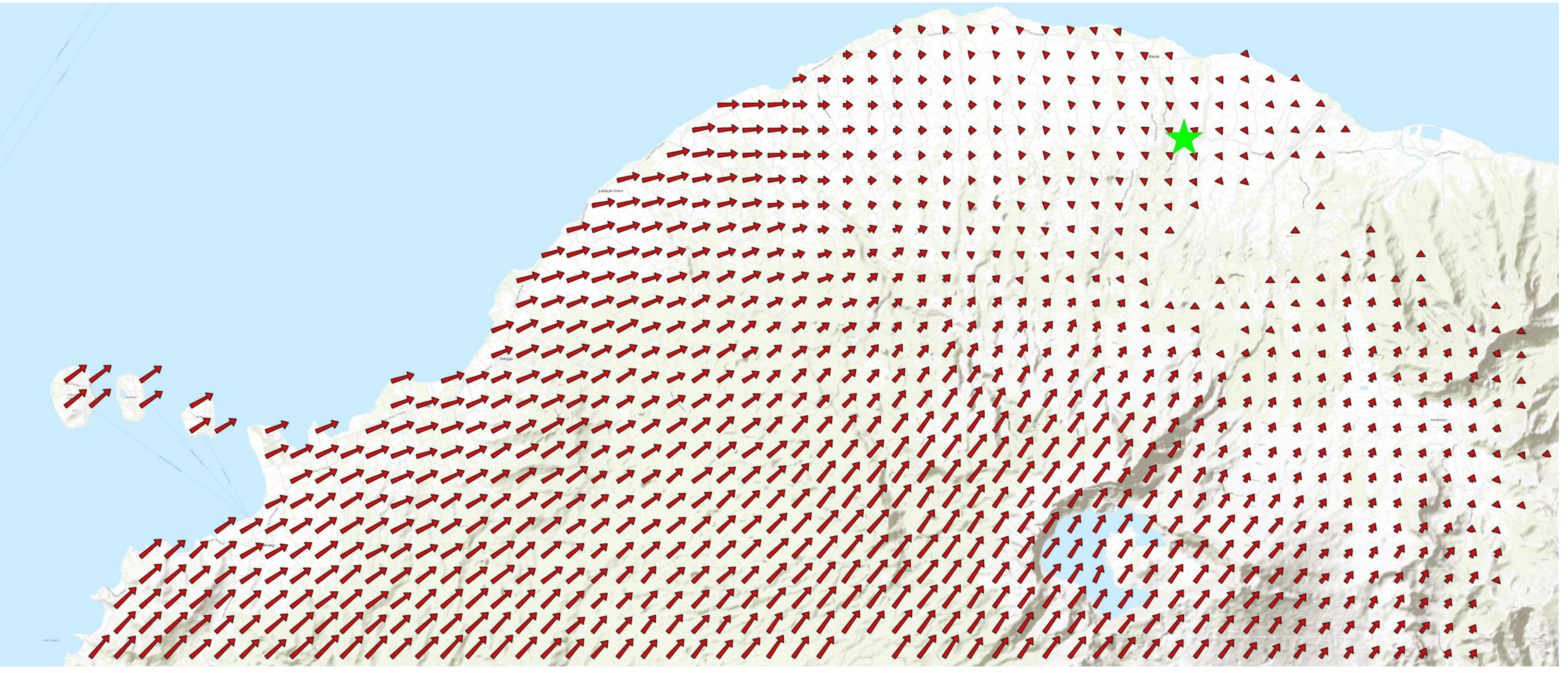


Figure 5. Result of the calculation for horizontal components

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