Evidence of ground deformation in Sri Lanka: A study using SBAS InSAR Time-series

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Abstract *In a previous study the author has used the combined permanent scatterer (PS) interferometry (PS-InSAR) and differential interferometry (D-InSAR) methods to detect displacement due to low-magnitude (5.5 ≥ M) earthquakes in Sri Lanka. This study extends these previous findings using small baseline subset (SBAS) InSAR time-series technique for measuring slow surface displacement during the period from 2017-01-07 to 2024-04-29. The reason for this investigation is because of the continuation of the low magnitude earthquakes in the central region of the island as well as the upsurge in the occurrences of high magnitude earth quakes in the vicinity of the Indian ocean. A series of Sentinel 1A images were employed to investigate the deformation pattern all around the country. In this paper the SBAS results for the study area concentrated in the central province is presented. The method provides corrections for unwrapping errors. Further it inverts the raw phase time series and apply corrections for tropospheric and atmospheric noises to retrieve the displacement time series. A careful selection of the stable reference point with highest spatial coherence (>0.8) for the interferogram stack is employed to detect the relative ground motion. The cumulative LOS displacement was observed in the range of +20cm as uplift and -40cm as subsidence. Motion transects are also provided indicating the movement velocities resulting from the possible land deformation. According to the investigation, the western regions of the central mountains show an uplift while the south eastern regions suggest significant subsidence. The regions prone to subsidence are the candidate regions prone to heavy landslides in Sri Lanka according to the NBRO ground-based landslide inventories.*

Keywords:SBAS, InSAR time series, Ground Deformation, Land Slides, Earthquakes

Introduction

Deformation on land can be considered as upward or downward movements (Yuan et al., 2021). This is a complex geological phenomenon occurring due to changes in the Earth's surface, which can involve uplift, subsidence, or lateral movements. In islands like Sri Lanka, factors that could cause such phenomena can be due to tectonic activities in the region (Figure 1) resulting due to the proximity to the boundary of the Indian and Australian tectonic plates, coastal processes such as erosion and sediment deposition along coastlines altering land elevations, groundwater extraction which is excessive pumping of groundwater, mining, gravity variations, infrastructure projects causing localized deformation. Moreover, natural sediment compaction in delta regions or due to soft soils and rising sea levels in coastal areas especially due to artificial islands like Colombo port city project could trigger deformation (Fernandez et al., 2009; Welikanna & Jin, 2023).

Time series Interferometric Synthetic Aperture Radar (InSAR) techniques have proven to be very effective in detecting these land deformations in the past (Prati et al., 2010). The possibility of applying these methods for large areas with millimeter-level precision, had made them very effective to detect land deformation. Mainly two advanced InSAR techniques stand out in its proven performance in detecting subtle ground movements. They are, Persistent Scatterer InSAR (PSInSAR) and Small Baseline Subset InSAR (SBASInSAR). Though they are proven to be robust application of them in challenging environments such as islands is still requiring certain efforts (Welikanna & Jin, 2023).

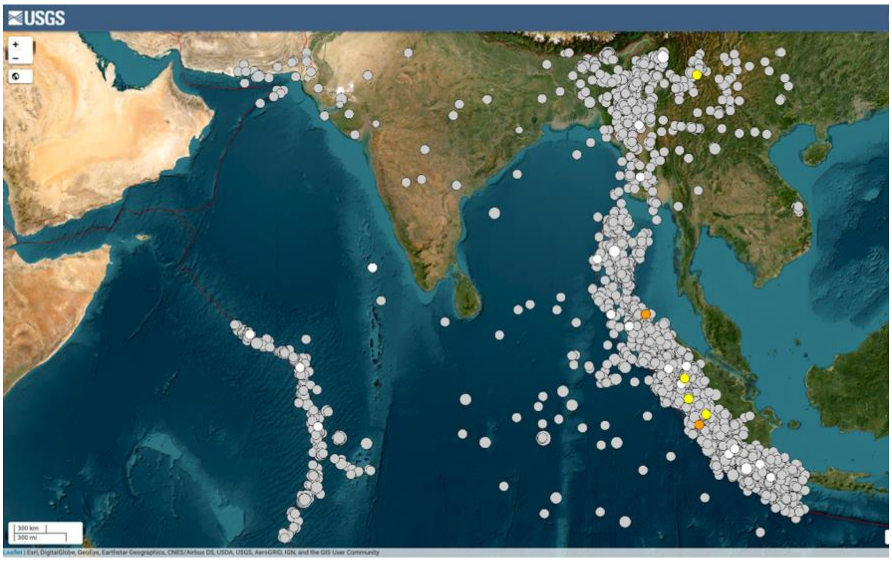

Figure 1: Significant increase in earthquake surrounding Sri Lanka (Source USGS).

Methodology:

Principally, InSAR utilizes the phase difference between two or more SAR images acquired at different times to measure ground displacement (Yunjun et al., 2019). Using this technique, it is possible to measure surface changes at centimeter levels over large areas. PSInSAR works on identifying and analyzing stable, point-like targets called persistent scatterers (PS) that maintain steady scattering properties over time. Manmade structure or stable natural feature such as rock outcrops are reliable candidates of being PS. Thus, this method can be considered a point cloud analysis. Even in the areas where significant temporal decorrelation between two SAR images exists, PS provide a feasible network to work, in order to identify the deformation patterns. In this method mainly, PS candidates are identified based on amplitude stability index or the coherence. A time-series analysis of PS points derives the temporal displacement. Atmospheric phase screen (APS) estimation and removal is a critical part to avoid long wavelengths being derived as deformation. The PSInSAR method is easy to apply on urban and rocky terrain conditions. For detail discussion on the method refer (Colesanti et al., 2003; Welikanna & Jin, 2023). In contrast to PSInSAR, SBASInSAR works on Distributed Scatters (DS) by utilizing multiple short baseline interferograms. By using these short baselines, the method aims to reduce spatial and temporal decorrelation effects. This technique is mostly useful in areas where PS is difficult to detect. Further, in high altitude terrains with moderate vegetation, SBASInSAR is considered effective and more successful over PSInSAR (Beccaro et al., 2023; Han et al., 2023; Hrysiewicz et al., 2023; Lauknes et al., 2010; Zhang et al., 2023). The main considerations in SBASInSAR are the selection of SAR image pairs with small spatial and temporal baselines. Then use these images to generate a network of interferograms and by performing network inversion to derive displacement time series.

Applications of these advanced InSAR methods to island land masses are important (Fernandez et al., 2009). Large spatial coverage on wide-areas makes these methods useful. Thus, these methods have the ability to monitor entire coastlines and inland areas concurrently. By executing this sensitive method carefully and it is possible to determine millimeter level movements to identify delicate tectonic or anthropogenic deformation. Long-term monitoring capabilities provide the possibility to distinguish between seasonal variations and long-term trends. It is possible to say that these two methods are complementary to each other. PSInSAR is seen to excels in urban areas, while SBASInSAR performs well in rural settings (Lauknes et al., 2010). InSAR methods are a useful alternative to ground-based monitoring networks using methods like Continuous Operating Reference Stations (CORS) using GNSS or precise levelling.

Challenges are met in applying these methods accurately, due to atmospheric effects, vegetation and limited PS density in tropical islands (Massonnet et al., 1994). Due to significant atmospheric variability, in islands these methods require robust correction methods (APS). Tropical vegetation in many island environments can limit InSAR effectiveness, needing careful selection of images and processing parameters. As a whole, in island terrains due to the difficulty of identifying PS, integration of PSInSAR and SBASInSAR methods might be important to get a reliable deformation estimation(Yuan et al., 2021).

Materials and Methods

The study was conducted using two sets of ascending and descending geometry timeseries composed of Sentinel 1 SAR imagery. Descending time series was chosen from the 09th January 2020 to 31st December 2023, while the ascending data set spanned from 01st January 2020 to 01st December 2023. Both the time series was constrained to have 12 days of temporal base line and a spatial baseline within 150m as thresholds. Consequently, there were 108 pairs of short base line interferogram used for both the analysis. By using the ascending and descending combination the deformation velocities along the two SAR LOS directions could be measured. Details of the data sets are given in the Table 1.

Table 1: Details of the SBAS time series used for the study

Time	Geometry	Path	Frame	No of pairs	Spatial Baseline	Temporal Baseline
2020-01-09 to 2023-12-31	Descending	19	566	108	(0-150) m	12 Days
2020-01-01 to 2023-12-01	Ascending	27	15	108	(0-150) m	12 Days

SBASInSAR processing

SBASInSAR is a time series analysis using compound master satellite images (Beccaro et al., 2023). The land deformation profiles are deduced using minimal temporal and spatial baseline separated interferometric pairs (Zhang et al., 2023). Comparing to the PSInSAR method the use of multiple master images in SBASInSAR promise an optimized coherence environments for the selection of DS. Further it requires a smaller number of SAR images then the PS method reducing the volume of the data storage (Welikanna & Jin, 2023). SBASInSAR is a prominent choice in determining land subsidence particularly in mountainous regions with vegetation cover (Beccaro et al., 2023; Yuan et al., 2021; Zhang et al., 2023). SBASInSAR method mainly includes correcting for unwrapping errors and inverting for raw phase time series and correcting for noise from multiple sources. The following flow chart (Figure 2) shows the method in detail implemented in OpenSARLab from the (Alaska Satellite Facility, https://asf.alaska.edu/asf-services-open-science-lab/).

SBASInSAR involves the following main steps. Prepare data by selecting the appropriate SAR data from the ASF archive (Yunjun et al., 2019). Conduct preprocessing to improve the geolocation accuracy using precise orbits and coregister all SAR images to a mutual master image (the study used the earliest image of the stack). Using the temporal and spatial baseline thresholds (Table 1), creating a network of interferograms, and perform multilooking to reduce noise and computational cost. Implement phase unwrapping on each interferogram (SNAPHU algorithm) (Chen & Zebker, 2002). Careful selection of a stable reference point to determine the relative deformation measurements. Make SBAS Inversion by constructing and solving the SBAS linear equation system to deduce displacement time series. Perform singular value decomposition (SVD) to get a robust solution for SBAS equation. Estimate and remove APS using spatial-temporal filtering. Finally, a post-processing to apply additional filters to reduce noise. More theoretical details refer ((Yunjun et al., 2019; Zhang et al., 2023).

Figure 2: Methodological flow for the execution of the SBASInSAR analysis over the Sri Lankan terrain

Results and Discussion

The master images for interferometric stacking were chosen based on their specific dates and orbits. The earliest images, 2020-01-09 and 2020-01-01 for the descending and ascending orbits, were chosen as master images respectively. The reference points were selected using the criteria; coherence > 0.85. A point located at Kandy railway station with REF_LAT': '7.10882442131242', 'REF_LON': '79.90510268408387' and a point located on a major road in the east coast having REF_LAT 6.871648622359203 REF_LON 81.83144844593917 was taken as reference points for the descending and the ascending images respectively. Spatial coherence as seen in Figure 3 (a), (c) suggest high in the range of 0.8 to 1 in urban areas, rural settlements and along the major roads. Land cover and the heterogeneous topography in these regions effect the spatial coherence determination. These observations are typical due to the presence of stable, man-made structures that are good radar reflectors. This suggests reliable measurements in urban areas for urban subsidence or structural stability. However, this could lead to a bias in results towards urban areas if rural areas have significantly lower coherence. Temporal coherence (Figure 3 (b), (d)), suggest higher values in the same range but in slightly different settings close to be semi urban and rural terrains. This indicates very stable scattering characteristics over time in these semi-urban regions. It provides the feasibility for long-term deformation monitoring in semi-urban zones, with consistent and reliable measurements. Potential reasons could be the mix of built structures and vegetation in semi-urban areas. This might provide a balance of stable scatterers and consistent land cover. Understanding and the need of detail analysis over the coherence patterns is important. The contrast between urban and rural terrain coherence can affect the completeness and reliability of the deformation maps deduced. The edge effects due to the change in coherence at the boundaries between urban and rural areas working as transition zones may show significant deformation patterns as well.

Interferogram network design influences the ability to capture deformation at different timescales. Short temporal baselines are influenced by atmospheric noise but better for capturing rapid deformation. On the other hand, longer, temporal baselines are useful for detecting long-term trends but subjected to temporal decorrelation in less coherent areas.

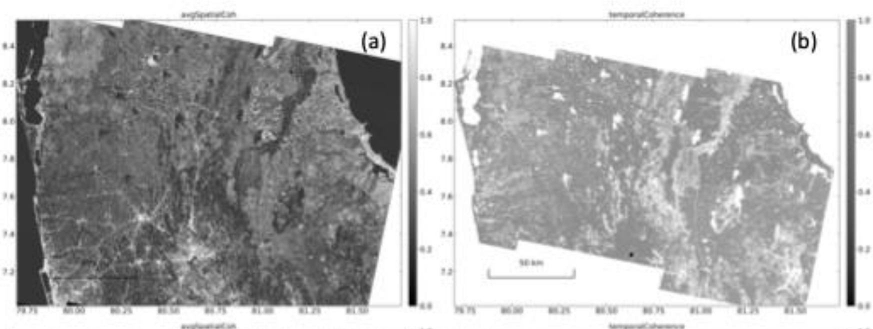

Figure 3: Average spatial and the temporal coherence used to determine the DS base SBASInSAR analysis for descending (a), (b) and ascending geometries (c), (d)

The effect of interferogram network density is an important factor to consider in the determination of robust results using SBASInSAR method. Denser networks in high-coherence areas can provide better results in urban and semi-urban zones. On the other hand, sparser networks in low-coherence areas can lead to less reliable or missing data in rural or vegetated regions. The interferogram network used is the study and the baseline and coherence history are provided in the figure below. Average spatial coherence for both ascending and descending lie in the range 0.5-0.6, while a reasonable number of small baselines interferogram were used to suite bot the urban and suburban regions.

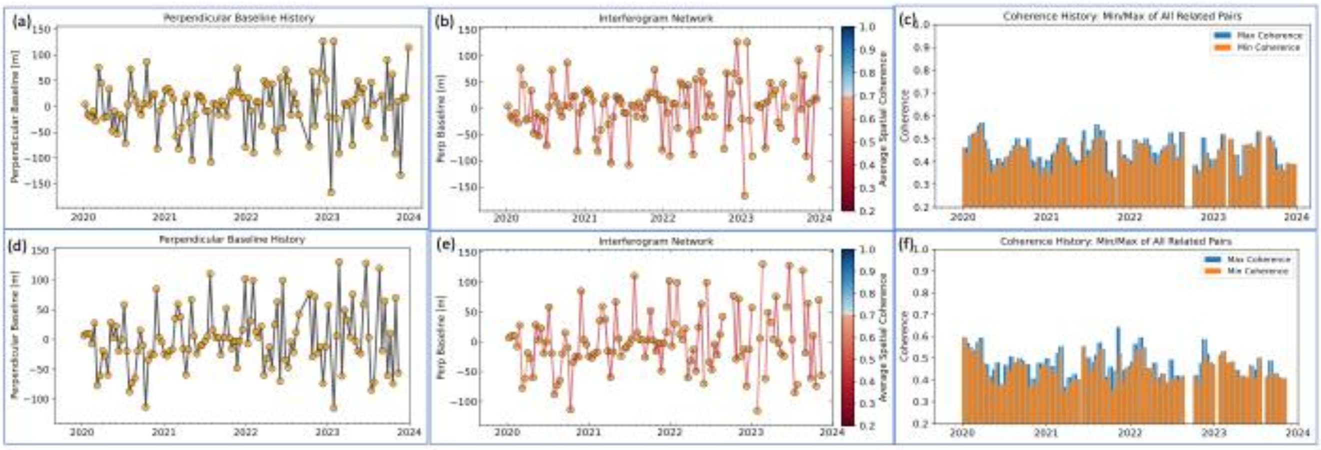

Figure 4: Perpendicular baseline, interferogram network and the coherence history used for descending (a), (b), (c) and ascending geometries (d), (e), (f).

Higher network redundancy in coherent areas, allows better error estimation and more reliable deformation measurements. Lower redundancy in less coherent areas, can lead to greater uncertainty or gaps in the velocity field. The spatial coverage owing to the work is comprehensive in urban and semi-urban areas. Further the results could be patchy or less reliable in rural or heavily vegetated areas. Accuracy and precision according to the coherence and the network used is high in built-up areas, accounting to high spatial coherence. Additionally, it could be good in semi-urban areas with high temporal coherence, but potentially lower or more uncertain in other areas.

Figure 5: LOS velocity profiles along the transects for the descending geometry

The deformation patterns deduced using the study are sown in figure 5 and 6 for descending and ascending geometries respectively. The deformation detected is subjected to following constraints. It is likely to capture urban-specific phenomena better (e.g., building subsidence, infrastructure stability). The results have shown good capability for detecting gradual changes in semi-urban areas. Further, the detection might miss or contain higher uncertainty for deformation in rural or natural landscapes. According to the reference point selected in descending geometry near the “Kandy railway station”, it is possible to see the regions to the south east show’s subsidence in the range of -2 cm/year to -12 cm/year along the descending LOS. The western coastal region suggest uplift in the range +2 cm/year to +7cm/year along the descending LOS. According to the descending LOS direction these areas show westward movement away from the satellite. While the movements detected in the ascending geometry can be meaningfully interpreted by the ascending geometry as its inverse, where the same movements suggest and uplift.

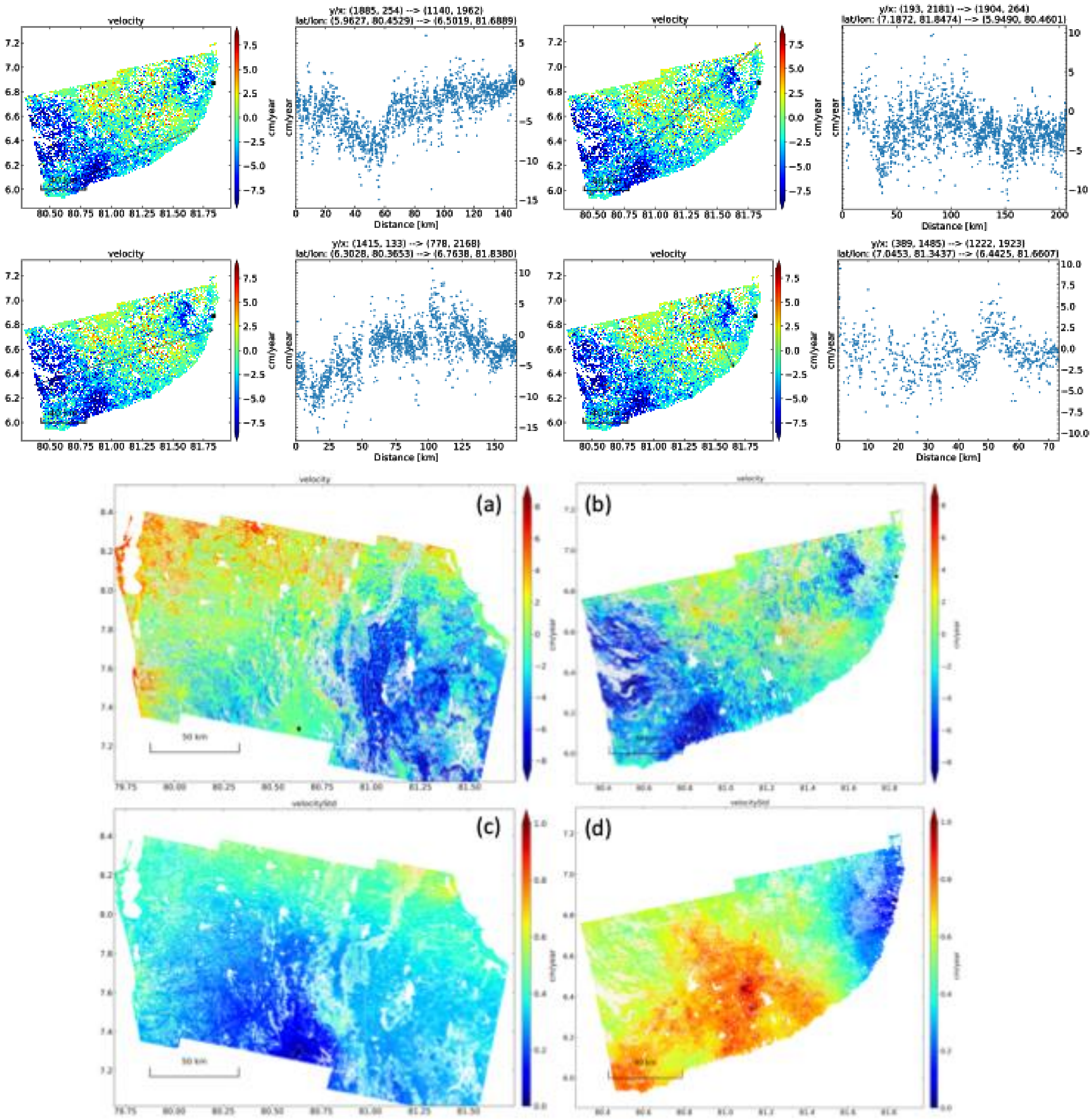

Figure 7: Resulting average terrain velocity and the estimated error in the velocity determination measured using the SBASInSAR for the central mountain regions of Sri Lanka in the descending (a) (c) and the ascending (b) (d) geometries respectively.

According to the results the average terrain velocity detected from the analysis suggest possible land deformation to the south-central region of the country. These regions are heavily affected by landslides and includes the provinces having the highest candidacy for human evacuations. Significant uplifts can be seen along the west coast especially in the descending geometry, while in the ascending geometry a more stable coastal region can be seen. According to Figure 6, in the southern coast possible uplift can bee seen especially in the areas where the port constructions had been carried out. These observations are more elaborated in Figure 7 and Figure 8. The study continues to investigate these velocity profiles patterns and their correspondence to the underlying geological structures or human activities.

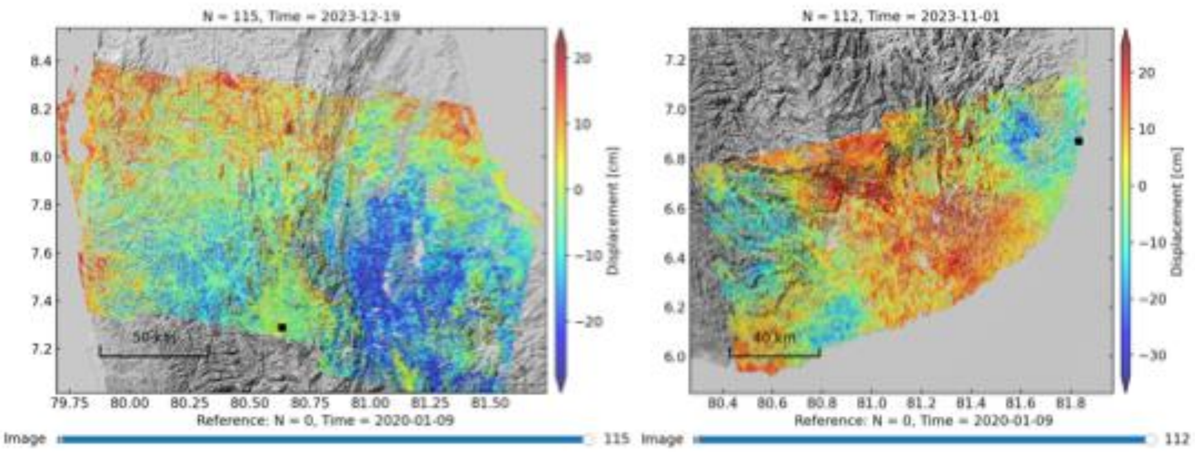

Figure 8: Determined velocity estimations draped over the base SRTM DEM 30m DEM, for the considered two geometries.

The velocity Standard error (Figure 7 (c) and (d), define the spatial distribution of velocity uncertainties. As a whole, in the analysis the overall standard error lies in the range 0.3 for the descending deformation results and around 0.4 for the ascending results. Areas with high standard deviations close to 1.0 could be seen in the ascending results, possibly due to the low temporal coherence. Though it is difficult to suggest the effect of atmosphere in the results at this stage, its contribution might have led to these slightly higher error sources. As one main drawback of the application of time series InSAR analysis in Sri Lanka, the missing ground-based monitoring in the form of CORS or precise levelling practices, hinders the detail validation of the detected deformation. As obvious from the analysis the regions suggest possible land deformation. The areas prominent with its uplift and subsidence require further monitoring or investigation.

Conclusion:

PSInSAR and SBASInSAR offer powerful tools for detecting and monitoring ground deformation in island environments. Using the SBASInSAR method, in this study we have investigated the evidences for possible subsidence in the central and the southern regions.

The detected significant deformation regions correspond to heavily landslide activated areas of Sri Lanka. Other than that these areas are subjected to limestone mining and collapsed earth quake recordings. By leveraging the strengths of each technique and addressing the unique challenges of island settings, studies can gain unique insights into effect of the tectonic activity in the region, coastal processes, and anthropogenic impacts on ground stability. Integrating PSInSAR along with SBASInSAR for urban areas to maximize the use of high spatial coherence and the possibility of studying advanced filtering or multi-temporal methods to improve results in lower coherence areas is important. Adjusting the interferogram network to balance coverage between different land cover types could be an important step the way forward. Finally, the causes for the deformation existence, mainly due to mining, low gravity, tank and water body induced seismic activities and increasing number of major earthquakes in the vicinity of Sri Lanka as well as inside the island need to be further studied.

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