DEM GENERATION USING INTERFEROMETRIC SAR

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ABSTRACT:

Digital Elevation Models (DEMs) are critical for terrain analysis, hydrological modeling, disaster risk assessment, and land-use planning, especially in mountainous regions like Nepal. Conventional DEM generation methods such as field surveying, photogrammetry, and LiDAR are often costly and impractical in remote areas. Interferometric Synthetic Aperture Radar (InSAR) has emerged as a viable and cost-effective alternative, capable of generating high-resolution DEMs with vertical accuracies of 1–3 m RMSE. This study presents a comprehensive InSAR-based DEM generation workflow for a region covering Muglin and the surrounding central Himalayan terrain of Nepal using Sentinel-1 Single Look Complex (SLC) images acquired on May 10 and May 22, 2024, with a 12-day temporal baseline. The study area was defined by the available Sentinel-1 scene footprint, extending approximately from 84.04°E to 85.22°E longitude and 27.53°N to 29.21°N latitude, encompassing diverse topographic conditions ranging from the mid-hills around Muglin to higher Himalayan regions. The methodology involves coregistration, interferogram formation, Goldstein phase filtering, SNAPHU-based phase unwrapping, and phase-to-height conversion, producing a 10 m resolution DEM. The generated DEM was validated against ASTER DEM reference data at nine ground control points. The resulting Root Mean Square Error (RMSE) of approximately 52 m highlights the challenges posed by steep and complex Himalayan terrain, including geometric distortions such as layover, foreshortening, and shadow effects. Despite these limitations, the study establishes a reproducible InSAR processing framework applicable to geospatial and hazard-related applications in Nepal and similar mountainous environments.

1 INTRODUCTION

Digital Elevation Models (DEMs) are fundamental datasets used for terrain analysis, hydrological modeling, disaster risk assessment and land-use planning. Accurate elevation information is particularly important in mountainous countries like Nepal, where steep terrain and frequent hazards such as landslides and floods require reliable topographic information (Gaire et al., 2015; Scott Watson et al., 2019). Conventional DEM generation methods include field surveying, photogrammetry, and LiDAR; however, these approaches are often expensive and difficult to implement in remote mountainous regions. Remote sensing techniques have therefore become widely used for large-scale elevation mapping. Among these techniques, Interferometric Synthetic Aperture Radar (InSAR) has emerged as a powerful method for DEM generation—(Lu et al., 2007). InSAR derives terrain elevation by measuring the phase difference between two Synthetic Aperture Radar (SAR) images acquired from slightly different viewing geometries. One of the early comprehensive explanations of DEM generation using satellite SAR interferometry was presented by paper (Zhong et al., 2013)who described the interferometric processing chain and discussed factors affecting DEM accuracy such as baseline errors, atmospheric effects, and phase unwrapping uncertainties.Several studies have attempted to improve DEM extraction algorithms from interferometric data. For example, (Gao et al., 2017)proposed a multi-look iterative algorithm that first generates a coarse DEM and then refines it through successive iterations to improve spatial resolution while reducing phase noise. Their results demonstrated improved elevation accuracy compared with conventional multilooking approaches.

Other researchers have investigated interferometric DEM generation using different SAR sensors.For example, (Li et al., 2018)developed an interferometric processing method for Gaofen-3 SAR data that balances phase noise reduction and spatial detail preservation. Their results demonstrated that optimized multilooking and interferometric processing could improve phase quality while minimizing resolution loss, leading to DEMs with enhanced vertical accuracy and terrain representation.

The repeat-pass interferometry experiments using SAR data reported that DEMs generated from interferometric processing can achieve vertical accuracies of several meters in flat regions, although the accuracy decreases in mountainous terrain due to geometric distortions and decorrelation effects (T. Zhang et al., 2017). Similarly, the joint use of multi-orbit high-resolution SAR data for DEM generation found that combining interferometric observations from different orbital geometries can significantly reduce atmospheric phase errors and improve vertical accuracy(L. Zhang et al., 2014).

Recent research has also focused on improving interferogram quality to enhance DEM generation. A non-local filtering technique for interferometric data obtained from the TanDEM-X Mission, resulted that advanced filtering methods can effectively reduce noise while preserving terrain details(Baier et al., 2018).

Despite significant progress in DEM generation using Interferometric Synthetic Aperture Radar, most existing studies focus on algorithm development or applications in well-studied regions.

Applications of InSAR-based DEM generation in the Himalayan region, particularly in Nepal, remain limited due to complex terrain and challenging environmental conditions. Therefore, it is important to evaluate the applicability of InSAR techniques for DEM generation in this region.The objective of this study is to develop and demonstrate a practical methodology for generating a DEM using SAR interferometry for a Nepal scene. The study utilizes SAR data from Sentinel-1 SLC images and applies interferometric processing techniques including interferogram generation, filtering, phase unwrapping, and phase-to-height conversion. The proposed workflow aims to provide a clear and reproducible framework for DEM generation using InSAR data, which can support future terrain analysis and geospatial applications in Nepal.

2 DATA AND METHODOLOGY

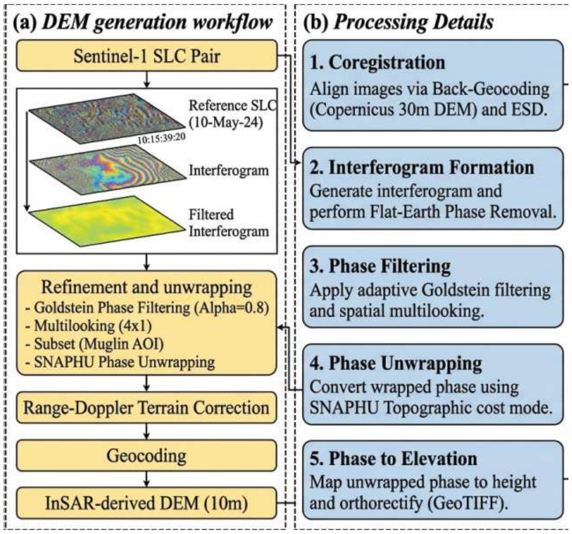


Figure 1. Methodological Chart

2.1. Data

For the DEM generation workflow, we used Sentinel-1 SAR data acquired over the study area in Muglin, Nepal. The area of interest (AOI) was defined by a polygon shapefile in WGS84 coordinates.

Type	Remarks
Sentinel 1 SLC Pair	Reference (Master): 5/10/2024
	Secondary (Slave): 5/22/2024
ASTER DEM	30 m for Validation

Table 1. Dataset Used

Category	Parameter	Value
SAR Pair	Temporal Baseline	12 days
	Orbit Direction	Descending
	Subswath	IW2
	Polarization	VV
Processing Parameters	Coherence Window	20 (range) × 5 (azimuth)
	Goldstein Filter	Alpha = 0.8
	Multilook	4 (range) × 1 (azimuth)
	SNAPHU Phase Unwrapping	4 × 4 tiles, 4 parallel workers, mask < 0.10 coherence

Table 2. Parameters

2.2 Principles of InSAR DEM Generation

Digital Elevation Models (DEMs) can be generated from the interferometric phase of two SAR acquisitions. The measured interferometric phase is composed of several components:

$$\phi Int = \phi Topography + \phi Change + \phi Movement + \phi Atmosphere \; \#\#(1)$$

For DEM generation, it is assumed that no surface displacement occurs between acquisitions, so the interferometric phase is dominated by topography:

$$\phi Int \approx \phi Topography + \phi Noise \; \#(2)$$

Where,

$$\phi Noise = \phi Change + \phi Atmosphere \; \#(3)$$

The unwrapped interferometric phase $\phi Topography$ is then converted into absolute height values relative to the WGS84 ellipsoid:

$$DEM\ (height) = f(\phi Topography, B, \theta) \; \#(4)$$

Here:
B= interferometric baseline
θ = radar look angle
f = geometric conversion from phase to height
This assumption ensures that the derived DEM represents the terrain elevation without influence from surface motion or atmospheric effects.

2.3 Workflow

2.2.1. Coregistration: The methodology begins with the alignment of the reference and secondary Sentinel-1 Single Look Complex (SLC) images. Precise orbit vectors are applied to update the state vectors. Alignment is achieved via **Back-Geocoding**, which uses the Copernicus 30m Global DEM to account for topographic effects. For the Terrain Observation by Progressive Scans (TOPS) acquisition mode, Enhanced Spectral Diversity (ESD) is implemented to ensure azimuth shift correction with an accuracy exceeding 0.001 pixels, preventing phase jumps between bursts.

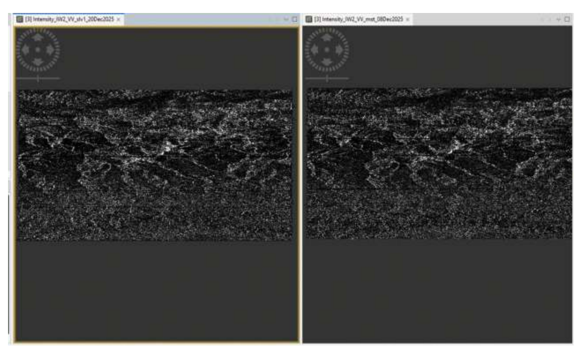


Figure 2. Applied Corregistration in Reference and Secondary SLC product

2.2.2. Interferogram Formation:
An interferogram is generated by multiplying the reference image by the complex conjugate of the secondary image. This step includes Flat-Earth Phase Removal, which eliminates the phase contribution related to the Earth's curvature based on a reference ellipsoid. This ensures that the remaining phase relates primarily to the topography and potential atmospheric delays.

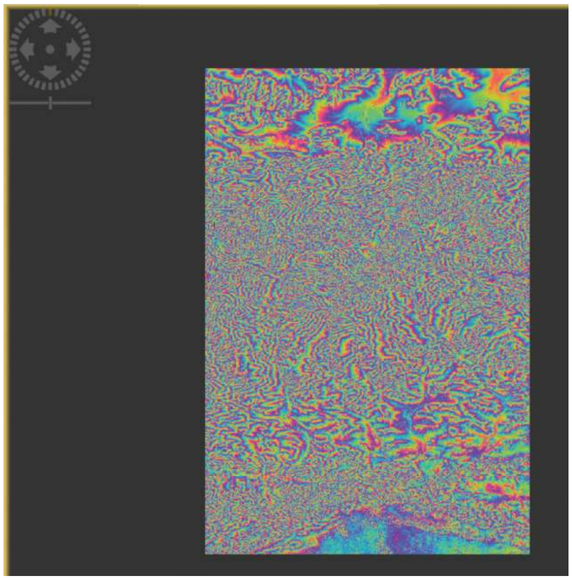


Figure 3. Phase Interferogram before Terrain Correction

2.2.3. Phase Filtering: To enhance the signal-to-noise ratio, Goldstein Phase Filtering is applied to the interferogram. This adaptive filtering technique reduces decorrelation noise caused by temporal or spatial baseline effects. Subsequently, Multilooking is performed (e.g., a 4:1 range-to-azimuth ratio) to reduce speckle noise and produce approximately square pixels, followed by a spatial Subset to the specific study area coordinates.

2.2.4. Phase Unwrapping: The filtered phase remains "wrapped" within the [-pi +pi] interval. To recover the continuous phase, the data is exported to the SNAPHU (Statistical-cost, Network-flow Algorithm for Phase Unwrapping). The algorithm uses a Topographic cost mode to resolve the integer 2π ambiguities, converting the fringe patterns into a continuous phase ramp representing the terrain.

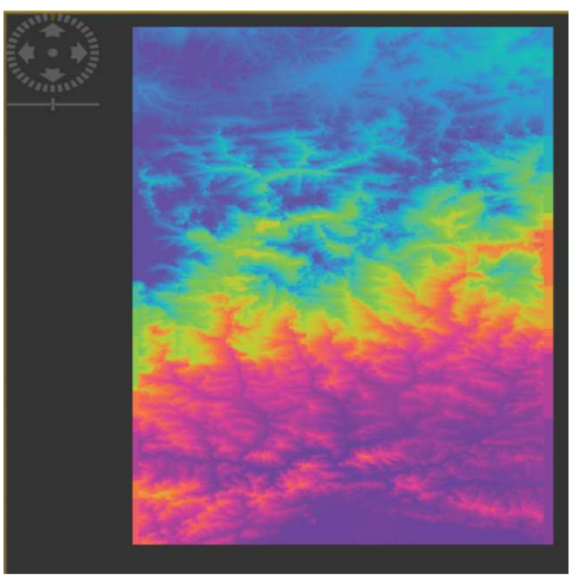


Figure 4. Phase Unwrapping using SNAPHU before Terrain Correction

2.2.5. Phase to Elevation (DEM Generation): The unwrapped phase is converted into absolute height values relative to the WGS84 ellipsoid. This transformation utilizes the interferometric geometry (baseline and look angle) to map phase values to elevation. Finally, Range-Doppler Terrain Correction is applied to orthorectify the data, transforming it from the radar's slant-range geometry into a geocoded GeoTIFF in a geographic coordinate system.

2.2.6. Validation: The InSAR-derived DEM was validated using the ASTER DEM as a reference dataset to evaluate its elevation accuracy. Elevation values from both DEMs were compared at selected sample points, and the differences were calculated to assess consistency between the two datasets.

3 RESULT AND ANALYSIS

The DEM generated using InSAR, with a spatial resolution of 10 m, is presented below.

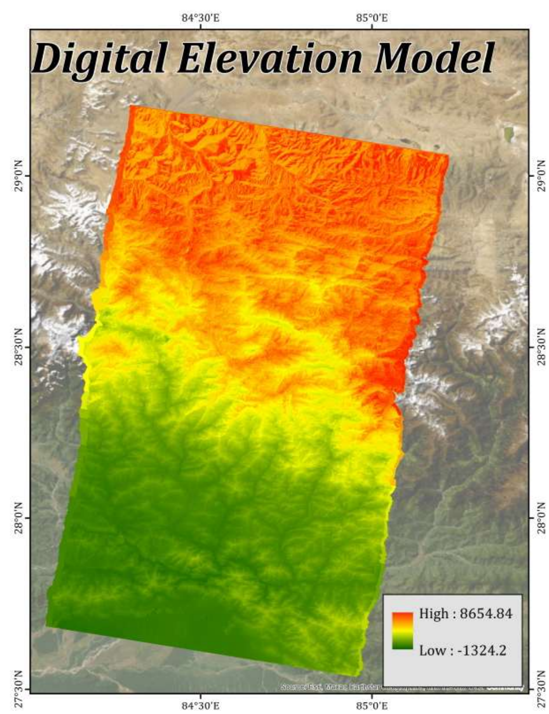
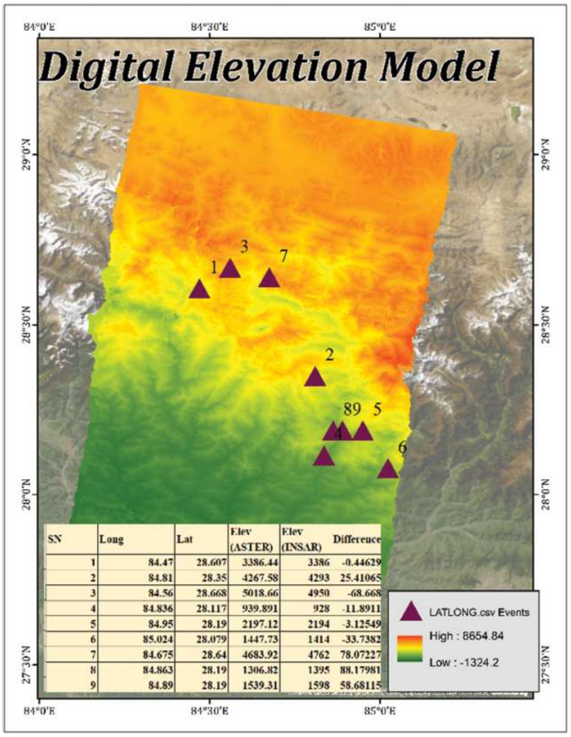


Figure 5. Digital Elevation Model

3.1 Validation

Ten points were selected to analyze the InSAR-derived DEM by comparing it with the ASTER DEM, as shown below.



SN	Long	Lat	Elev (ASTER)	Elev (INSAR)	Difference
1	84.47	28.607	3386.44	3386	-0.44629
2	84.81	28.35	4267.58	4293	25.41065
3	84.56	28.668	5018.66	4950	-68.668
4	84.836	28.117	939.891	928	-11.8911
5	84.95	28.19	2197.12	2194	-3.12549
6	85.024	28.079	1447.73	1414	-33.7382
7	84.675	28.64	4683.92	4762	78.07227
8	84.863	28.19	1306.82	1395	88.17981
9	84.89	28.19	1539.31	1598	58.68115

Figure 6. Cross Validation between Generated DEM and ASTER DEM

RMSE=

$$\sqrt{662.9185} \approx 51.61\text{m}\#(5)$$

An RMSE of ~52 m is relatively high for 10 m InSAR DEM resolution. These may correspond to steep slopes or layover areas. This is the strong limitation of the project.

4 LIMITATION AND RECOMMENDATION

The accuracy of the generated DEM is influenced by several inherent limitations of InSAR processing. Phase unwrapping errors may introduce unrealistic or negative elevation values, particularly in areas with low coherence or steep topography. DEM quality is also strongly dependent on the selection of SAR image pairs, as temporal decorrelation and unfavorable perpendicular baselines can reduce interferometric coherence and degrade elevation accuracy. In mountainous regions such as Nepal, geometric distortions including layover, foreshortening, and radar shadow are common and can significantly affect the reliability of the derived elevations. Furthermore, atmospheric phase delays introduce additional uncertainties that may propagate into the phase-to-height conversion process, resulting in elevation errors, especially over large spatial extents.

Future studies may improve DEM accuracy through several approaches that have been successfully demonstrated in previous research. Multi-temporal InSAR techniques such as Persistent Scatterer InSAR (PS-InSAR) and Small Baseline Subset (SBAS) methods have been shown to reduce noise and decorrelation effects by exploiting multiple SAR acquisitions (Berardino et al., 2002; Ferretti et al., 2001). Advanced interferogram filtering methods, including non-local filtering, have been reported to improve phase quality while preserving terrain details, leading to more accurate DEM generation(Baier et al., 2018). The use of ascending and descending orbit combinations can help mitigate geometric distortions and improve terrain representation in mountainous environments(L. Zhang et al., 2014). Additionally, higher-resolution SAR sensors such as TerraSAR-X and COSMO-SkyMed have demonstrated improved DEM accuracy compared with medium-resolution systems due to their finer spatial resolution (Rizzoli et al., 2017). Atmospheric correction techniques based on GNSS observations or numerical weather models have also been shown to reduce phase-delay-related errors(Hanssen, 2001). Finally, increasing the number of ground validation points and integrating InSAR-derived DEMs with existing elevation products such as SRTM or ALOS DEM may further enhance accuracy and reliability for applications including landslide susceptibility assessment, flood modeling, and terrain analysis.

5 CONCLUSION

This study successfully demonstrates an InSAR-based DEM generation workflow for Muglin, Nepal, using Sentinel-1 SAR data. The methodology, encompassing coregistration, interferogram generation, phase filtering, SNAPHU unwrapping, and terrain correction, produced a 10 m resolution DEM. Validation against ASTER DEM yielded an RMSE of approximately 52 m, reflecting the inherent challenges of complex Himalayan terrain, including layover and atmospheric effects. Future improvements should include multi-temporal InSAR approaches, advanced filtering techniques, higher-resolution SAR sensors, and increased ground control points to enhance elevation accuracy and broaden the applicability of InSAR-derived DEMs for hazard monitoring and land-use planning in Nepal.

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