Understanding the Influence of DEM Vertical Accuracy on Sentinel-1 Geolocation Performance

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Abstract

Digital Elevation Models (DEMs) are fundamental for ensuring the geolocation accuracy of Synthetic Aperture Radar (SAR) imagery, as vertical errors in elevation data propagate into horizontal displacements. This study examines the impact of DEM accuracy on the geolocation performance of Sentinel-1 Ground Range Detected (GRD) products over an urban area in Ankara, Türkiye. A comparative analysis was conducted using four global DEMs (SRTM 1″, SRTM 3″, AW3D30, Copernicus 30 m), a high-resolution national DEM (YÜKPAF), and two interferometrically derived DEMs generated from Sentinel-1 Single Look Complex (SLC) pairs. Vertical accuracy was validated against ICESat-2 ATL08 reference elevations, with Copernicus (2.2 m RMSE) and YÜKPAF (3.2 m RMSE) providing the highest reliability, while the InSAR-derived DEMs showed larger errors (>12 m) due to coherence loss and phase unwrapping inconsistencies. Horizontal accuracy was evaluated using Ground Control Points (GCPs) obtained from HGM-Küre. The results demonstrated that high-quality DEMs, particularly YÜKPAF, achieved the lowest horizontal RMSE (8.2 m), whereas InSAR-based DEMs produced the largest errors, approaching 15 m. Despite these variations, all orthorectified outputs remained below 15 m geolocation error, owing to the precise orbital information of Sentinel-1 and the flat topography of the study area. Overall, the study confirms that DEM quality is a decisive factor for SAR geolocation accuracy and offers practical guidance for dataset selection in operational SAR orthorectification workflows.

1. Introduction

Since the early 1980s, SAR has become a key component of Earth observation, supporting applications such as disaster management, environmental monitoring, and defense. Unlike optical sensors, which depend on sunlight and clear skies, SAR is an active microwave system that collects data regardless illumination, enabling consistent temporal monitoring even in persistently cloudy regions or during night-time. Beyond its capacity for uninterrupted imaging, SAR provides two complementary sources of information: amplitude, used for land cover classification and target detection, and phase, which supports precise elevation modelling and displacement analysis through interferometric techniques.

Despite these advantages, the side-looking geometry of SAR introduces geometric distortions not encountered in nadir-viewing optical systems. Common phenomena include foreshortening, where slopes facing the radar appear compressed; layover, where elevated objects are displaced toward the sensor; and shadowing, where terrain features block illumination and leave areas without data (Hanssen, 2001). Such effects can misrepresent the true location of features and complicate integration with other geospatial datasets (Boccardo et al., 2004). To mitigate these issues, orthorectification is applied, transforming radar measurements from slant range to geographic coordinates by incorporating orbital data, sensor geometry, and a DEM. GCPs, when available, further refine positional accuracy (Shimada, 2010).

The quality of the DEM is particularly decisive in this process. Even small vertical errors can cause horizontal displacements, especially at steep incidence angles (Fritz and Eineder, 2008). While widely available global DEMs such as SRTM offer standardized coverage, their resolution may not suffice for high-precision applications. By contrast, national high-resolution DEMs generally provide improved accuracy, although they are not always accessible. Alternatively, DEMs generated directly from SAR interferometry provide geometric consistency with the radar data but are sensitive to temporal decorrelation, phase unwrapping errors, and atmospheric effects.

In this context, the present study evaluates how DEM accuracy influences the geolocation performance of Sentinel-1 imagery. Several DEM sources; global, national, and InSAR-derived are assessed over an urban test site in Ankara, Türkiye. Vertical accuracy is validated against ICESat-2 ATL08 reference elevations, while horizontal accuracy is evaluated using GCPs. The study aims to quantify the relationship between DEM quality and geolocation error in low-relief terrain and to provide practical recommendations for DEM selection in SAR processing workflows.

2. Study Area and Data

2.1 Study Area

The research was conducted in a central urban district of Ankara, Türkiye, located at approximately 39.98°N and 32.75°E. The study site spans nearly 28 km² and is dominated by dense urban structures, including clusters of high-rise residential and commercial buildings, extensive paved surfaces, and limited green areas (Figure 1).

The terrain is relatively flat, with slopes generally below 20%, which reduces the likelihood of large-scale terrain distortions in SAR imagery. Nevertheless, localized effects such as radar layover and shadowing remain evident, caused by vertical man-made features and narrow street corridors. These characteristics make the site particularly suitable for investigating the influence of DEM accuracy on the positional quality of orthorectified SAR products.

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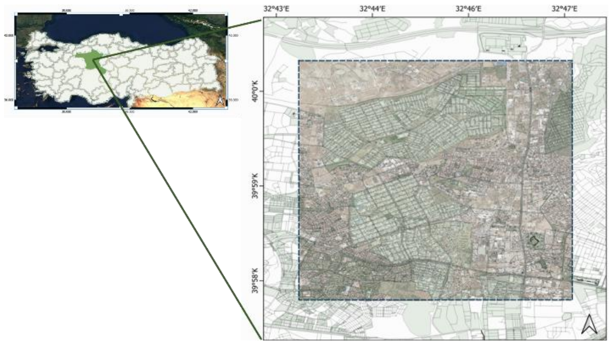

Figure 1. Study area in central Ankara, Türkiye.

2.2 Data Used

This study used a Sentinel-1 GRD image acquired on 1 August 2024 in Interferometric Wide (IW) mode during a descending orbit (Table 1).

To assess the impact of elevation data on orthorectification, six different DEMs were evaluated. Four of them were open-source available datasets with different spatial resolutions and production methods (i.e., SRTM 1″, SRTM 3″, ALOS AW3D30, and YÜKPAF). Additionally, two InSAR-based DEMs were generated using Sentinel-1 SLC images acquired on 1 and 13 August 2024 (Table 1). These DEMs were produced using two different reference models (i.e., Copernicus and SRTM 3″) to examine how reference DEM selection influences elevation accuracy.

Vertical accuracy of each DEM was assessed using 495 ATL08 elevation points from NASA's ICESat-2 mission (Figure 2). For horizontal accuracy, orthorectified outputs were compared GCPs obtained from Türkiye's HGM Küre platform.

Images	Acquisition time	Pass	Pixel Spacing Range/Azimuth (m)
GRD	08/25/2024 03:50:37	Descending	10 /10
SLC (Master)	08/01/2024 03:50:36	Descending	2.33/ 13.93
SLC (Slave)	08/13/2024 03:50:36	Descending	2.33/ 13.93

Table 1. Sentinel-1 image parameters used in the study

Figure 2. Spatial distribution of ICESat-2 ATL08 reference elevation points within the study area.

3. Methodology

The methodological design of this study was structured to systematically evaluate the influence of DEM accuracy on Sentinel-1 geolocation performance. The workflow consisted of three major stages: (i) assessment of DEM vertical accuracy using ICESat-2 data, (ii) generation of InSAR-based DEMs from Sentinel-1 SLC pairs and vertical accuracy valuation using ICESat-2, (iii) orthorectification of Sentinel-1 GRD imagery using different DEMs, and validation of horizontal accuracy against reliable GCPs.

3.1 Validation of External DEM Vertical Accuracy

The first step focused on external DEMs including SRTM 1″, SRTM 3″, AW3D30, Copernicus 30 m, and YÜKPAF. Their elevation values were validated against 495 ICESat-2 ATL08 points after filtering out outliers caused by steep slopes, vegetation canopy returns, or low-quality signals. Accuracy was quantified using standard statistical measures: Root Mean Square Error (RMSE) and the linear error at 90% confidence level (LE90), as defined in Equations (1) and (2).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i^{measured} - x_i^{true})^2} \quad (1)$$

$$LE_{90} = 1.6449 \times \text{RMSE} \quad (2)$$

where, n is the number of observations, x_i measured is the estimated DEM elevation for the i-th sample, and x_i true is the reference elevation from ICESat-2.

The coefficient 1.6449 corresponds to the z-score of a standard normal distribution at the 90% confidence level. When elevation errors follow a normal distribution, LE90 provides a statistically consistent and interpretable measure of vertical accuracy.

3.2 Generation of InSAR-based DEMs

The study also investigated the potential of producing elevation models directly from Sentinel-1 imagery using interferometric techniques. InSAR-based DEMs are attractive because they do not rely on external elevation data and are intrinsically consistent with the SAR acquisition geometry. This geometric consistency is particularly valuable for applications such as deformation monitoring, co-registration of time-series, or areas where up-to-date elevation information is unavailable.

However, the achievable accuracy of interferometric DEMs is strongly influenced by acquisition geometry and environmental conditions. Factors such as baseline length, temporal decorrelation, atmospheric phase delays, and unwrapping errors can significantly degrade the final product. Coherence loss further constrains DEM quality and can be categorized into several types (Moreira et al., 2013): temporal decorrelation, arising from changes in surface properties such as vegetation or soil moisture between acquisitions; volume decorrelation, caused by scattering within distributed volumes such as forest canopies; geometric decorrelation, resulting from differences in viewing geometry or large baselines, particularly in rugged terrain; and thermal decorrelation, which originates from sensor noise and instrumental limitations.

A key parameter controlling InSAR DEM quality is the height of ambiguity (HoA), which describes the vertical distance corresponding to a 2π phase cycle. HoA is inversely proportional to the perpendicular baseline B⊥ according to:

$$h_{amb} = \frac{\lambda R sin(incidence\ angle)}{n\ B_{\perp}} \tag{3}$$

where n (for repeat-pass = 2, for single-pass =1), B⊥ is the perpendicular component of the baseline between the two acquisitions. A larger B⊥ increases the sensitivity of the phase to topographic height but also raises the risk of spatial decorrelation and phase ambiguity (Wu and Madson, 2024).

Smaller HoA values provide greater height sensitivity but increase the risk of decorrelation, whereas larger HoA values reduce vertical precision. For Sentinel-1, with a C-band wavelength of 5.6 cm and repeat cycle of 12 days, the trade-off between coherence and vertical sensitivity is a central limitation for DEM generation.

The interferometric workflow was implemented in ESA SNAP and included co-registration of the master and slave images, interferogram formation, coherence estimation, Goldstein filtering, phase unwrapping, and terrain correction (Figure 3). Coherence maps were analyzed as an indicator of interferometric quality. Areas of low coherence, particularly over vegetated and rapidly changing surfaces, were prone to noise and phase inconsistencies, which introduced errors in the unwrapped phase and reduced the accuracy of the final DEM. In urban regions with stable backscatter, coherence levels were higher, resulting in more reliable elevation estimates.

Phase unwrapping was carried out using the minimum cost flow algorithm to resolve the 2π ambiguities. The unwrapped phase values were then converted into absolute elevations using the radar acquisition geometry. Importantly, a reference DEM is required in this step to align the relative heights. To evaluate the influence of the reference dataset, two different models were employed during geocoding: Copernicus DEM (30 m) and the SRTM 3″ DEM (90 m) were used to investigate the effect of reference model selection on the final product.

The generated DEMs were geocoded into WGS84/UTM Zone 36N and resampled to 30 m spatial resolution for consistency with the global datasets. Although the workflow produced elevation models covering the entire study area, the results were notably affected by coherence variations over built-up and vegetated surfaces. These limitations illustrate the challenges of InSAR DEM generation from C-band Sentinel-1 data, especially in urban environments, and highlight why external DEMs often provide superior accuracy. Nonetheless, including InSAR-derived products in the analysis allowed a meaningful comparison with global and national DEMs, revealing both the potential and constraints of this approach.

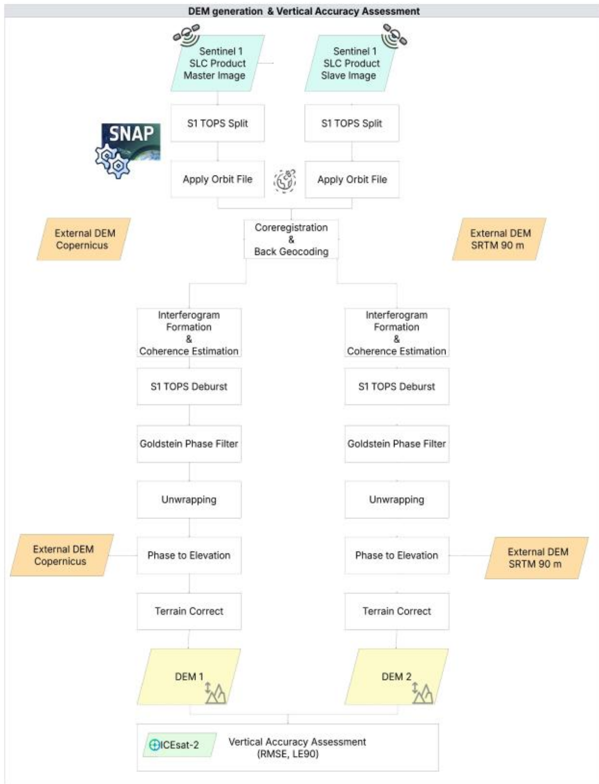

Figure 3. Methodology for InSAR-based DEM generation.

3.3 Orthorectification of Sentinel-1 GRD Imagery

Orthorectification was performed using the Range-Doppler Terrain Correction (RDTC) model implemented in ESA SNAP (Figure 4). RDTC is the standard approach for Sentinel-1 imagery.

In the RDTC, the slant-range distance measured by the sensor is projected to the Earth’s surface using DEM elevations, while the azimuth position of each pixel is refined from Doppler parameters and satellite velocity vectors. These corrections ensure that the final image is free from distortions such as foreshortening and layover, and that pixels are placed in their correct geographic locations. DEM quality directly influences this step: elevation errors propagate into horizontal displacements, and the magnitude of this effect depends on the incidence angle (Figure 5).

For consistency, all orthorectification experiments applied identical processing parameters and map projection settings. The only variable is the DEM input, which is the factor that allows the impact of elevation accuracy on geolocation performance to be isolated within the RDTC framework.

Horizontal geolocation accuracy was validated using Ground GCPs extracted from Türkiye’s HGM Küre platform. These points, selected from road intersections and building corners, provide a horizontal accuracy better than ±2.5 m at 90% confidence (Figure 6).

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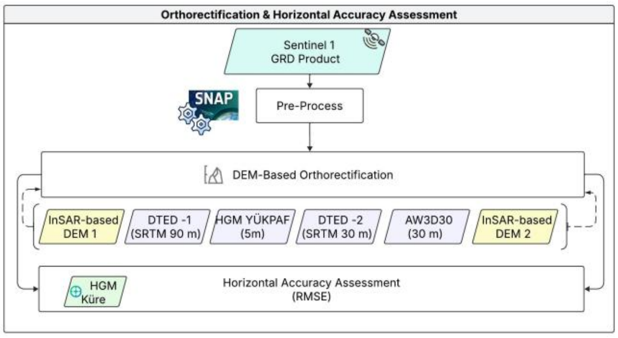

Figure 4. Processing workflow for orthorectifying Sentinel-1 SAR imagery.

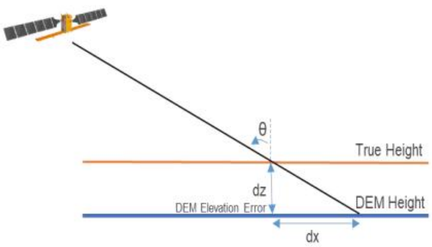

Figure 5. Influence of DEM accuracy on the planimetric accuracy (Oğuzhanoğlu, 2025).

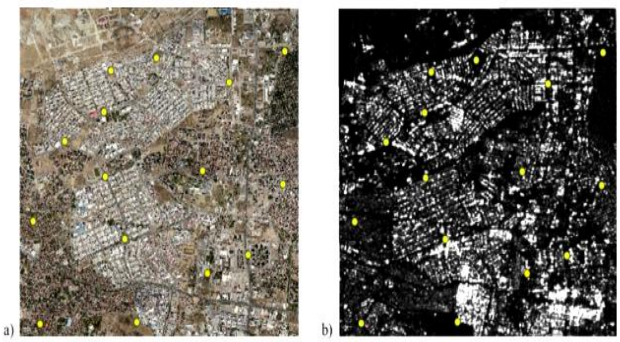

Figure 6. Spatial distribution of GCPs across the study area: (a) high-resolution natural color image, (b) orthorectified Sentinel-1 GRD image.

4. Applications & Results

The experiments were conducted to examine how DEM vertical accuracy affects the horizontal geolocation performance of Sentinel-1 orthorectification. The findings are presented in three stages: (i) evaluation of external DEM vertical accuracy, (ii) evaluation of InSAR-derived DEM vertical accuracy, and (iii) assessment of the horizontal accuracy of orthorectified Sentinel-1 GRD products.

4.1 Vertical Accuracy of DEMs

The validation of DEMs against ICESat-2 ATL08 reference elevations revealed notable differences in vertical accuracy across datasets (Table 2). Among the external models, the Copernicus DEM provided the highest accuracy with an RMSE of 2.2 m, while the national YÜKPAF DEM followed closely at 3.2 m. These results confirm the suitability of both datasets for applications requiring sub-5 m vertical accuracy.

In contrast, global DEMs such as AW3D30, SRTM 1″, and SRTM 3″ exhibited moderately higher errors, with RMSE values ranging between 5.2 and 5.8 m. Although these products still offer reasonable consistency for regional-scale analyses, their vertical accuracy is less reliable for applications demanding higher geolocation accuracy.

Overall, the results indicate that recent global products like Copernicus, supported by improved production methods and finer resolution, clearly outperform earlier global missions such as SRTM. The YÜKPAF DEM also demonstrates that national high-resolution products can achieve competitive accuracy levels, particularly valuable where local datasets are available.

DEM	Vertical Accuracy RMSE (m)	Vertical Accuracy LE90 (m)
SRTM 1 arc-second	5.2	8.6
SRTM 3 arc-second	5.8	9.6
AW3D30	5.5	9.1
YÜKPAF	3.2	5.3
Copernicus	2.2	3.6

Table 2. Statistical summary of vertical accuracy of external DEMs.

4.2 InSAR-based DEM Generation and Vertical Accuracy

Two interferometric DEMs were generated using Sentinel-1 SLC pairs acquired on 1 and 13 August 2024. Standard InSAR processing was applied, including co-registration, interferogram generation, coherence filtering, phase unwrapping, and terrain correction. A critical step was phase unwrapping, where ambiguities in the interferometric phase were resolved using auxiliary reference DEMs. To investigate the influence of auxiliary data, two reference DEMs (Copernicus 30 m and SRTM 3″) were tested during phase unwrapping and geocoding.

The results show that the choice of reference DEM has a measurable impact on the final interferometric product. The DEM generated with Copernicus as a reference achieved slightly better accuracy (12.9 m RMSE) than the one referenced to SRTM 3″ (14.6 m RMSE) (Table 3). This difference highlights the importance of employing a higher-resolution and more accurate reference DEM to constrain phase unwrapping.

DEM	Vertical Accuracy RMSE (m)	Vertical Accuracy LE90 (m)
InSAR-based DEM (Copernicus referenced)	12.9	21.3
InSAR-based DEM (SRTM 3 arc-second referenced)	14.6	24.1

Table 3. Statistical summary of vertical accuracy of InSAR-based DEMs

Nevertheless, both interferometric products exhibited considerably higher vertical errors compared to external DEMs. The reduced accuracy can be attributed to several well-known limitations of repeat-pass C-band interferometry: temporal decorrelation between the two acquisitions, sensitivity to baseline geometry, atmospheric phase disturbances, and phase unwrapping inconsistencies. These factors collectively degrade

coherence, particularly in vegetated and dynamic surfaces, leading to local noise and large-scale elevation biases.
The intermediate products of the InSAR workflow illustrate these challenges (Figure 7). The interferogram (Figure 7a) reveals the phase differences sensitive to surface topography, while the coherence map (Figure 7b) shows a clear reduction in vegetated and urban-fringe areas. The unwrapped interferogram (Figure 7c) exposes discontinuities where coherence is low, directly propagating into errors in the final DEM (Figure 7d). In contrast, stable urban areas maintained higher coherence, providing relatively more reliable elevation estimates.

Overall, the InSAR-derived DEMs demonstrate the potential of Sentinel-1 for topographic mapping but also underline the inherent limitations of C-band repeat-pass interferometry in urban environments. While their geometric consistency with SAR acquisitions is advantageous, the achieved accuracy (>12 m RMSE) falls short of that required for high-precision geolocation applications, reinforcing the need for external DEMs in orthorectification workflows.

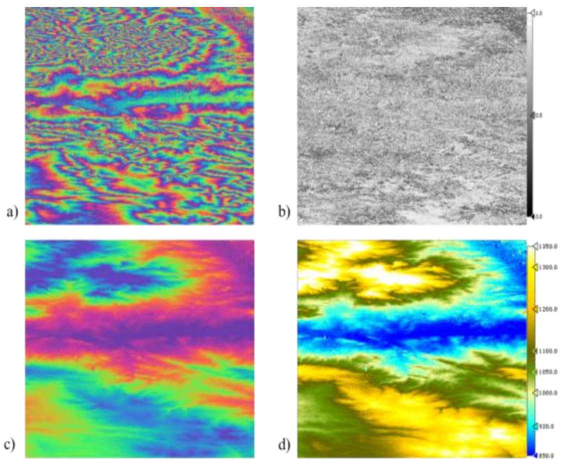

Figure 7. Main steps of InSAR method. (a) interferogram (b) coherence, (c) unwrapped interferogram, and (d) generated DEM.

4.3 Orthorectification and Horizontal Accuracy

To assess how DEM quality influences geolocation, Sentinel-1 GRD imagery was orthorectified in ESA SNAP using a fixed processing chain in which the DEM was the only variable. Horizontal accuracy was then validated against GCPs from Türkiye's HGM-Küre platform, representing road intersections and building corners with ±2.5 m at 90% confidence. This setup ensured that differences in positional accuracy could be attributed directly to the elevation input.

The results (Table 3) demonstrate a clear performance gradient among the tested DEMs. The national YÜKPAF model delivered the most accurate outcome, with an RMSE of 8.2 m, followed closely by the Copernicus DEM and other global datasets (SRTM 1″, SRTM 3″, AW3D30), which clustered between 9–10 m. These results highlight the added value of recent global and national products that provide finer spatial resolution and improved vertical fidelity. In contrast, the InSAR-derived DEMs produced substantially larger errors, exceeding 15 m RMSE. Their lower reliability stems from interferometric limitations such as temporal decorrelation and phase unwrapping inconsistencies, which degrade height estimates and propagate into horizontal displacements.

Table 3 provides a statistical summary, while Figure 8 illustrates how RMSE varies with elevation quality across DEM types. DEMs with higher vertical accuracy consistently reduced displacement vectors and produced tighter error distributions, whereas interferometric products exhibited broader and more scattered deviations. The spatial error patterns confirm that the propagation of vertical inaccuracies into the planimetric domain is systematic and strongly governed by DEM accuracy.

Although the quality differences between DEMs were evident, all orthorectified images achieved geolocation errors below 15 m. This robustness can be attributed to the precise Sentinel-1 orbital parameters and the low-relief topography of Ankara, which mitigate the amplification of elevation-induced distortions. Nevertheless, the results underline that DEM quality remains the dominant factor in determining the positional accuracy of SAR orthorectification, particularly in regions with more complex terrain where elevation errors would likely have a stronger effect.

Orthorectification with DEM	Horizontal Accuracy RMSE (m)
SRTM 1 arc-second	9.1
SRTM 3 arc-second	10.2
AW3D30	9.5
YÜKPAF	8.2
InSAR-based DEM (Copernicus referenced)	15.0
InSAR-based DEM (SRTM 3 arc-second referenced)	15.2

Table 3. Statistical summary of horizontal accuracy for Sentinel-1 GRD images orthorectified with various DEMs.

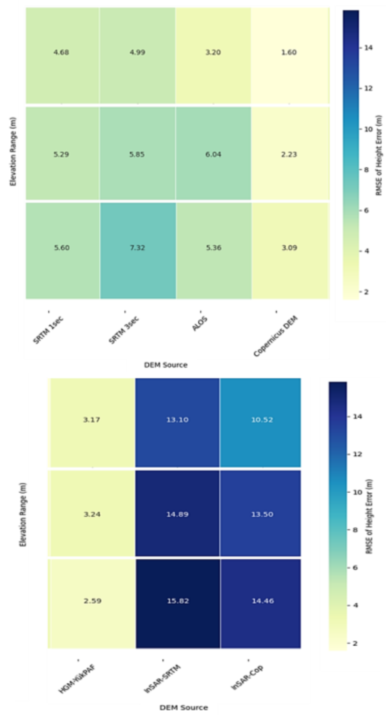

Figure 8. Elevation-dependent RMSE trends across different DEM types.

5. Conclusion

This study assessed how DEM accuracy influences the geolocation performance of orthorectified Sentinel-1 imagery. Vertical validation using ICESat-2 ATL08 elevations showed that recent high-quality DEMs offer clear advantages: the Copernicus DEM achieved the lowest error (2.2 m RMSE), closely followed by the national YÜKPAF model (3.2 m RMSE). In contrast, InSAR-derived DEMs exhibited markedly higher vertical errors (>12 m) due to coherence loss, phase unwrapping inconsistencies, and dependence on reference DEM quality.

When applied within the RDTC framework in ESA SNAP, these vertical discrepancies directly affected horizontal positioning. The YÜKPAF DEM yielded the most accurate orthorectification (8.2 m RMSE), while AW3D30 produced results in the 9–10 m range. Interferometric DEMs performed poorest (≈15 m RMSE), confirming that vertical errors propagate into planimetric displacements.

Overall, the findings highlight two key points. First, high-resolution national DEMs should be prioritized for SAR orthorectification, as they enhance geolocation accuracy beyond global standards. Second, InSAR-based DEMs, despite their geometric consistency with radar acquisitions, remain limited by environmental decorrelation and phase-processing uncertainties.

In relatively flat regions such as Ankara, the impact of DEM variability is moderate; all cases achieved sub-15 m geolocation accuracy owing to stable Sentinel-1 orbital parameters and homogeneous topography. However, DEM quality becomes increasingly critical in rugged terrain, where elevation errors are amplified by steeper incidence angles.

Overall, DEM accuracy is a fundamental control on orthorectified SAR quality, with direct implications for environmental monitoring, disaster response, and defense mapping. Future work should extend this evaluation to complex terrains and investigate advanced solutions such as multi-source DEM fusion and lidar–InSAR integration to further improve geolocation accuracy.

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