Accuracy Assessment of Sentinel-1 SAR-Derived DEMs: Comparative Analysis with SRTM and ALOS References

Ochirkhuyag Lkhamjav[1,3,4]*, Fuan Tsai[1,2]

[1] *Department of Civil Engineering, National Central University, Taoyuan 32017, Taiwan (ROC) - olkhamjav@g.ncu.edu.tw*

[2] *Center for Space and Remote Sensing Research, National Central University, Taoyuan 32017, Taiwan (ROC) – ftsai@csrsr.ncu.edu.tw*

[3] *Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar 15170, Mongolia - ochirkhuyag_l@mas.ac.mn*

[4] *Mongolian Geospatial Association, Ulaanbaatar 15141, Mongolia - ochirkhuyag@geomedeelel.mn*

Abstract: This study evaluates the accuracy of Digital Elevation Models (DEMs) derived from Sentinel-1 C-band Synthetic Aperture Radar (SAR) interferometry by comparing them with established global reference datasets—the Shuttle Radar Topography Mission (SRTM) and Advanced Land Observing Satellite (ALOS) DEMs. The validation was conducted over Darkhan-Uul province, Mongolia, using a stratified sampling approach with 500 validation points across diverse land cover types. Statistical metrics including Pearson correlation, Root Mean Square Error (RMSE), and descriptive statistics were employed. Results indicate that the Sentinel-1 DEM exhibits exceptional relative accuracy, with near-perfect correlation coefficients ($r > 0.999$) against both reference datasets. However, a systematic elevation bias of approximately 38–39 meters was observed, with RMSE values of 37.98 m (SRTM) and 39.47 m (ALOS). The low standard deviations (2.94–3.24 m) confirm high precision despite absolute offset. The study concludes that Sentinel-1 InSAR is highly reliable for relative elevation mapping but requires bias correction for absolute elevation applications.

Keywords: SAR, DEM, Sentinel-1, accuracy, topography

1. Introduction

Digital Elevation Models (DEMs), encompassing their variants Digital Terrain Models (DTMs) and Digital Surface Models (DSMs), provide essential geospatial data infrastructure supporting diverse applications ranging from hydrological modeling and geohazard assessment to urban planning, infrastructure development, and precision agriculture (Li et al., 2005; Guth, 2006). Synthetic Aperture Radar (SAR) technology has emerged as a transformative remote sensing capability for topographic mapping and surface change detection, offering distinct operational advantages over conventional optical and passive microwave systems (Bamler and Hartl, 1998; Rosen et al., 2000).

The fundamental advantages of SAR technology for surveying and mapping applications include: (1) all-weather operational capability, providing consistent data acquisition regardless of cloud cover or precipitation; (2) day-night imaging capacity, enabling flexible mission planning and rapid response capabilities; (3) penetration characteristics dependent on frequency and surface properties, allowing subsurface feature detection in specific conditions; and (4) coherent measurement capability, enabling interferometric applications for high-precision elevation and displacement measurements (Zebker and Goldstein, 1986; Massonnet and Feigl, 1998).Global topographic mapping missions utilizing InSAR technology have demonstrated the operational viability of SAR-based elevation model generation. The Shuttle Radar Topography Mission (SRTM), conducted in February 2000, employed simultaneous C-band and X-band interferometry to generate the first comprehensive near-global DEM at 30-meter spatial resolution (Farr et al., 2007).

This research addresses the critical need for systematic accuracy assessment of Sentinel-1 SAR-derived digital elevation models through rigorous comparison with globally recognized reference datasets. The study aims to: (1) quantify the absolute and relative accuracy of Sentinel-1 InSAR-derived DEMs against SRTM and ALOS reference standards; (2) characterize systematic error patterns and their statistical properties across diverse terrain conditions; (3) evaluate the geometric fidelity and topographic structure preservation capabilities of Sentinel-1 interferometry; and (4) provide recommendations for operational implementation and bias correction procedures.

The research contributes to the surveying and mapping community through comprehensive statistical validation methodology applicable to SAR-derived elevation products; quantitative accuracy parameters supporting mission planning and quality assurance procedures; identification of systematic bias patterns enabling correction algorithm development; and operational guidance for integrating Sentinel-1 DEMs within existing topographic mapping workflows.

2. Methodology

The study area encompasses Darkhan-Uul province, Mongolia (49.2°N - 49.8°N, 105.5°E - 106.8°E), representing diverse terrain characteristics essential for comprehensive DEM validation (Figure 1). The region exhibits elevation variations from 600 to 1,500 meters above sea level, encompassing steppe grasslands, forested areas, urban settlements, and bare ground surfaces. This topographic and land cover diversity provides representative conditions for evaluating SAR-derived elevation accuracy across varied scattering environments.

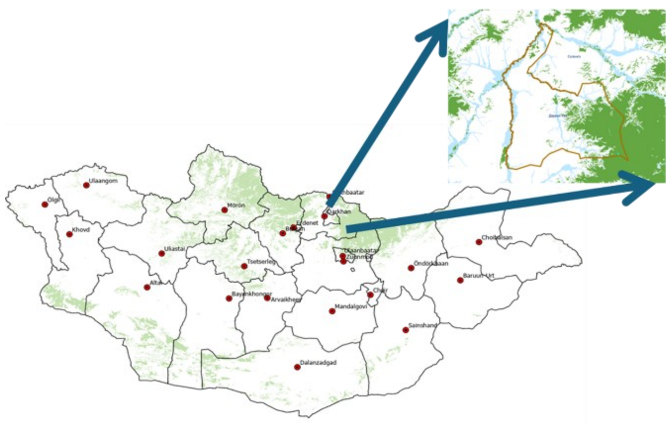

Figure 1. Study Area

Interferometric processing utilized ESA SNAP (Sentinel Application Platform) version 12 following standard InSAR workflow (Figure 2): (1) precise orbit file application for baseline refinement; (2) coregistration achieving sub-pixel alignment accuracy; (3) interferogram formation through complex multiplication; (4) coherence estimation for quality assessment; (5) adaptive filtering using Goldstein approach; (6) phase unwrapping via minimum cost flow algorithm; and (7) terrain correction and geocoding to WGS84 coordinate system.

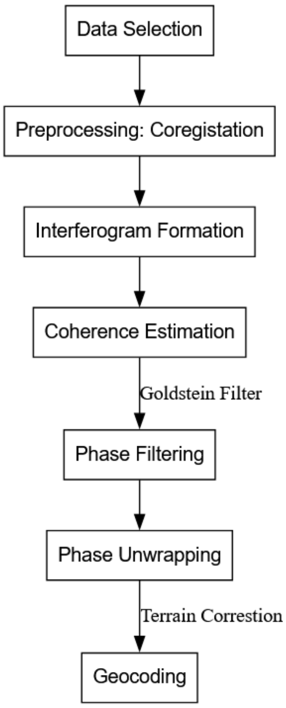

Figure 2. Flowcharts of approaches

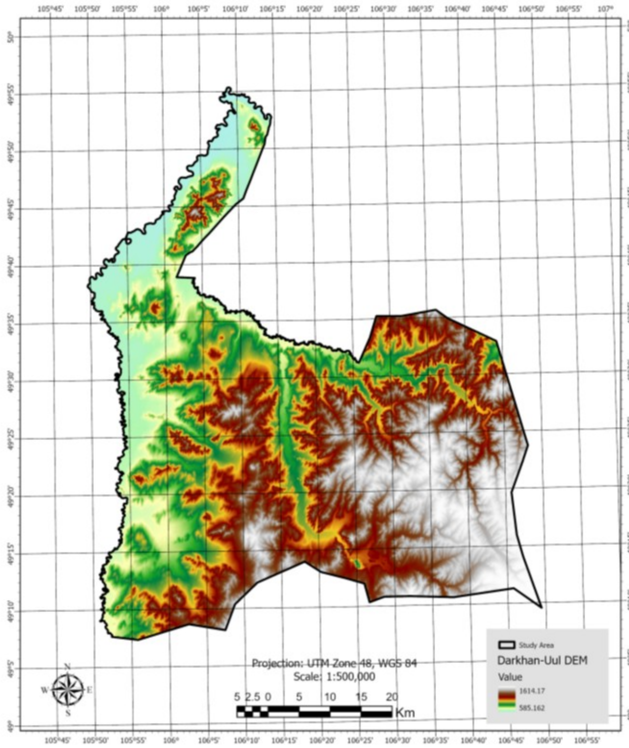

Figure 3. DEM generated from Sentinel 1 data, spatial resolution 10

3. Results and Discussions

The processing of Sentinel-1 (C-band, IW mode, GRD) datasets yielded distinct but complementary results, demonstrating the strengths and limitations of each system for different applications. Sentinel-1's wide swath enabled regional-scale analysis but suffered from decorrelation over long temporal baselines (Figure 3).

Results demonstrate that Sentinel-1 interferometry achieves exceptional geometric fidelity in topographic representation while exhibiting systematic elevation bias requiring calibration for absolute accuracy applications. The near-perfect correlations validate the technique's capability for relative elevation measurements essential for gradient-dependent applications such as hydrological modeling and geomorphological analysis. Systematic bias patterns suggest consistent error sources potentially including atmospheric phase delays, orbital parameter uncertainties, or geodetic datum inconsistencies. The reproducible nature of these errors enables correction algorithm development for operational implementations requiring absolute elevation accuracy.

In figure 4, the comparative analysis between the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model and the Digital Elevation Model derived from Sentinel-1 Synthetic

Aperture Radar (SAR) reveals a strong positive correlation across the examined elevation range. The scatterplot analysis demonstrates a linear relationship between the two datasets, with elevation values ranging from approximately 600 meters to 1,500 meters.

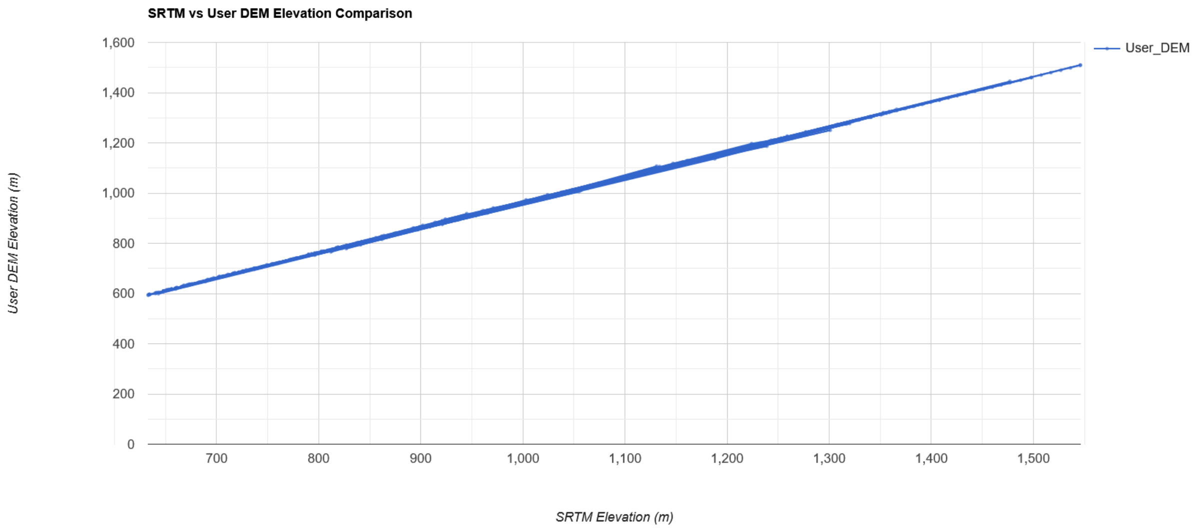

Figure 4. The comparison of SRTM DEM and DEM generated from Sentinel-1 data

Pearson correlation analysis revealed exceptionally strong linear relationships between Sentinel-1 derived elevations and reference datasets. Correlation with ALOS achieved $r = 0.9999$ ($p < 0.001$), while SRTM comparison yielded $r = 0.9998$ ($p < 0.001$). These near-unity correlations demonstrate preservation of topographic structure and relative elevation relationships. Statistical analysis identified consistent systematic elevation underestimation averaging 37.84 ± 3.24 meters relative to SRTM and 39.36 ± 2.94 meters relative to ALOS. The narrow standard deviations indicate high measurement precision despite absolute bias. Frequency distribution exhibits normal pattern centered at 38 meters, confirming systematic rather than random error characteristics. The RMSE calculations quantify overall elevation discrepancies: Sentinel-1 vs. SRTM yielded 37.98 meters RMSE, while Sentinel-1 vs. ALOS achieved 39.47 meters RMSE. Inter-reference comparison (ALOS vs. SRTM) demonstrated 4.06 meters RMSE, establishing baseline accuracy expectations between established datasets.

4. Conclusion

This study demonstrates that Sentinel-1 SAR interferometry can generate Digital Elevation Models with exceptional relative accuracy and topographic fidelity, as evidenced by near-perfect correlations with established reference datasets. The technique successfully preserves terrain structure and elevation relationships across diverse topographic conditions, validating its utility for applications requiring high-precision relative elevation information.

However, the presence of systematic elevation bias averaging 38-39 meters necessitates calibration procedures for applications demanding absolute elevation accuracy. The consistent nature of this bias, characterized by low variability and normal distribution patterns, facilitates straightforward correction through constant offset adjustment. Such calibration would enable the Sentinel-1 derived

DEM to achieve compatibility with established geodetic reference systems while maintaining its inherent geometric precision.

The findings support the operational deployment of Sentinel-1 interferometry for topographic mapping applications, particularly in regions where relative elevation accuracy is prioritized over absolute measurements. For absolute elevation applications, the implementation of bias correction algorithms based on local reference data would optimize the utility of SAR-derived elevation models. Future research should focus on understanding the sources of systematic bias and developing automated calibration procedures to enhance the absolute accuracy of interferometric DEMs while preserving their demonstrated geometric fidelity.

The validation framework employed in this study, incorporating multiple reference datasets and comprehensive statistical metrics, provides a robust methodology for assessing SAR-derived elevation accuracy and can serve as a template for similar validation studies in diverse geographic and topographic contexts.

References

Bamler, R. and Hartl, P. 1998. Synthetic aperture radar interferometry. *Inverse Problems*, 14(4), R1-R54.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. and Alsdorf, D. (2007). The Shuttle Radar Topography Mission. *Reviews of Geophysics*, 45(2), RG2004.

Guth, P.L. 2006. Geomorphometry from SRTM: comparison to NED. P*hotogrammetric Engineering & Remote Sensing*, 72(3), 269-277.

Li, Z., Zhu, C. and Gold, C. 2005. *Digital Terrain Modeling: Principles and Methodology*. CRC Press, Boca Raton.

Massonnet, D. and Feigl, K.L. 1998. Radar interferometry and its application to changes in the Earth's surface. *Reviews of Geophysics*, 36(4), 441-500.

Rosen, P.A., Hensley, S., Joughin, I.R., Li, F.K., Madsen, S.N., Rodriguez, E. and Goldstein, R.M. 2000. Synthetic aperture radar interferometry. Proceedings of the IEEE, 88(3), 333-382.

Zebker, H.A. and Goldstein, R.M. 1986. Topographic mapping from interferometric synthetic aperture radar observations. *Journal of Geophysical Research*, 91(B5), 4993-4999.