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

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МОНГОЛ УЛСЫН ШИНЖЛЭХ УХААНЫ АКАДЕМИ ГАЗАРЗҮЙ, ГЕОЭКОЛОГИЙН ХҮРЭЭЛЭН

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GEO SPATIAL

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ABSTRACT /Summary/

Accurate topographic mapping is vital for scientific, environmental, and engineering applications. Digital Elevation Model (DEM), including Digital Terrain Model (DTM) and Digital Surface Model (DSM), are essential for these purposes. Synthetic Aperture Radar (SAR) interferometry, particularly from Sentinel-1, offers significant potential for generating and updating DEMs due to its all-weather, high-resolution capabilities. This study conducts a comprehensive validation of Sentinel-1 SAR-derived DEMs by comparing them with established reference datasets, the Shuttle Radar Topography Mission (SRTM) and Advanced Land Observing Satellite (ALOS) DEMs, across diverse terrains (600-1,500 m elevation).

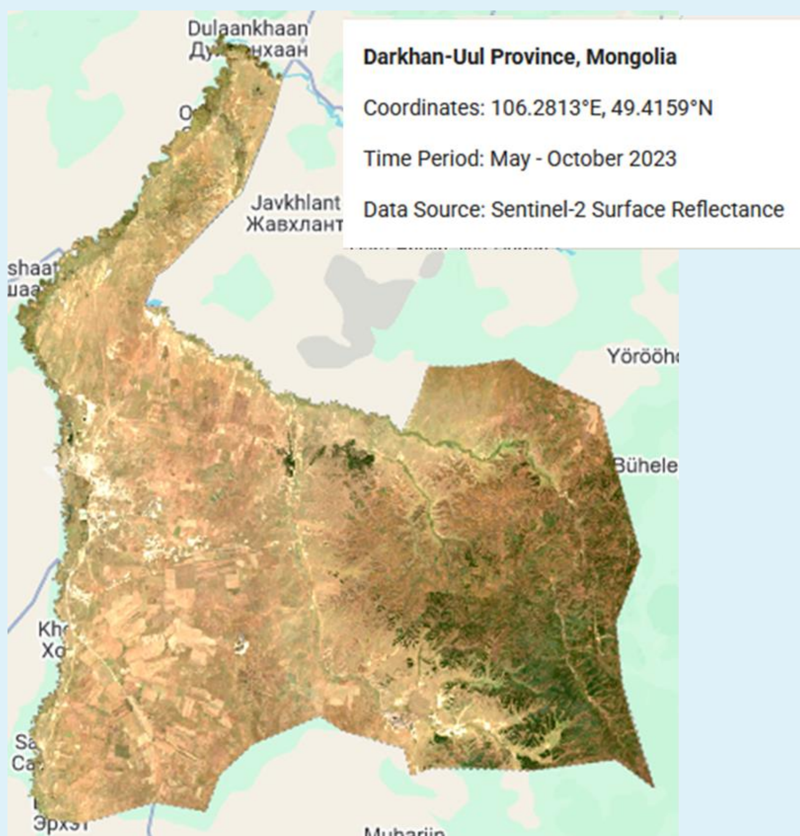
Using statistical metrics such as Pearson correlation, Root Mean Square Error (RMSE), and descriptive statistics, the research evaluates geometric fidelity and absolute elevation accuracy. Results indicate exceptional relative accuracy, with correlation coefficients (r > 0.999) for both reference datasets, confirming Sentinel-1^s ability to preserve topographic structure. However, a systematic elevation bias of 38-39 m was observed, with RMSE values of approximately 38-39 m and low standard deviations (2.94-3.24 m), indicating high precision despite absolute offsets. These findings suggest that while Sentinel-1 interferometry excels in relative elevation mapping, calibration is critical for absolute accuracy.

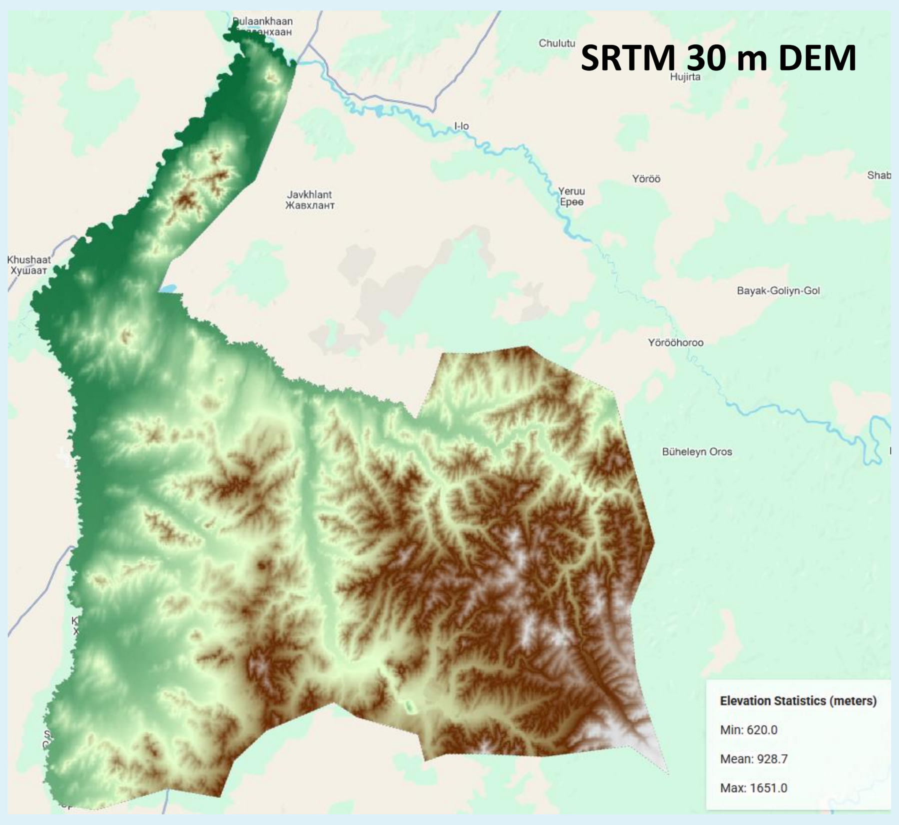
The study highlights Sentinel-1^s potential for supplementing global DEMs, particularly in low-vegetation environments. Terrain-specific bias corrections, advanced processing techniques like Persistent Scattered Interferometry, and sensor fusion with laser altimeter or multi-frequency SAR are recommended for enhanced accuracy. These insights provide a robust framework for operational topographic mapping, supporting applications in geosciences and environmental monitoring.

INTRODUCTION

- Digital Elevation Model (DEM): In its strictest definition, particularly within authoritative sources like the United States Geological Survey (USGS), a DEM represents the bare-earth topographic surface, excluding vegetation, buildings, and other above-ground features (USGS, 2023). However, the term is sometimes used generically to encompass various elevation models (Balz et al., 2021) or even interchangeably with Digital Surface Model (DSM) (Cloude, S. R, 2002).
- Digital Terrain Model (DTM): A DTM explicitly models the bare ground elevation, excluding vegetation and artificial structures (Hanssen, 2021). DTMs are essential for applications requiring terrain analysis, such as hydrology (flood modeling), geology (slope stability assessment), and civil engineering (Cloude, S. R, 2002).
- Digital Surface Model (DSM): Unlike a DTM, a DSM includes all surface features, such as trees, buildings, and infrastructure (JAXA, 2022). DSMs are widely used in urban planning (3D city modeling), forestry (canopy height estimation), and telecommunications (signal obstruction analysis) (Cloude, S. R, 2002).

STUDY AREA





MATERIALS AND METHODOLOGY

- Sentinel-1 C-band, descending, IW mode, GRD downloaded vie Copernicus Data Ecosystem
  - S1C_IW_SLC__1SDV_20250401T230640
  - S1B_IW_SLC__1SDV_20211218T230708
- SpaceTY MiniSAR Constellation: C-band, SM mode, 2 m spatial
  - BC2_SM_SLC_1SSV_20240725T035756
  - BC3-SM-SLC-1SVV-20250416T145927

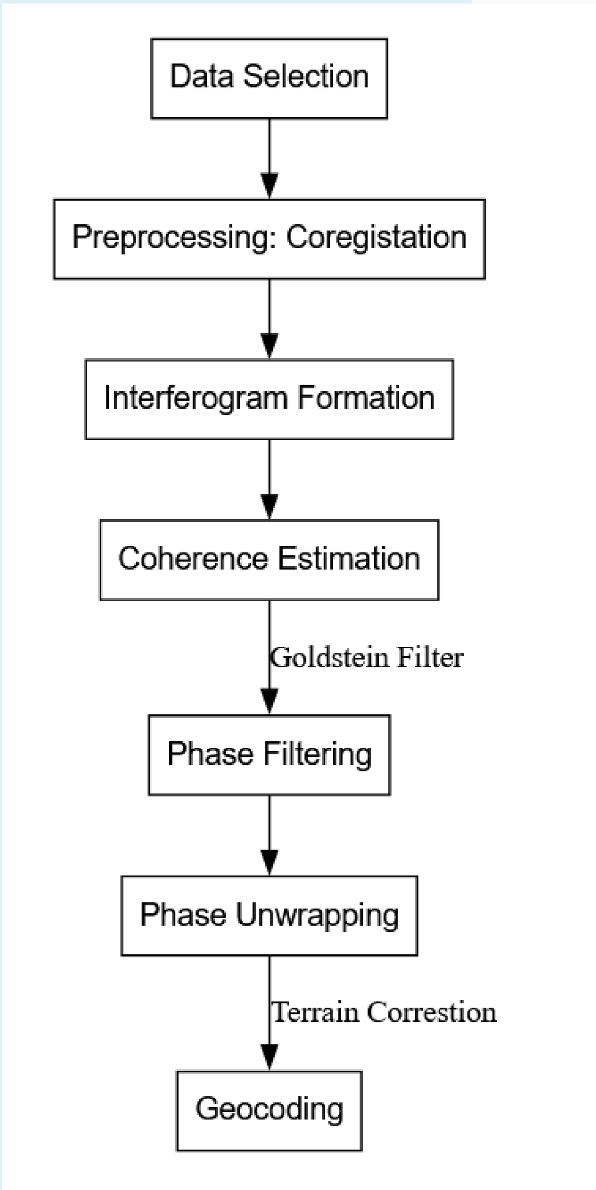
Two primary techniques leverage SAR data to derive three-dimensional surface information: Interferometric SAR (InSAR) and SAR Radargrammetry.

Interferometric SAR (InSAR): Principles and Workflow

- InSAR measures phase differences between two complex-valued SAR images acquired from slightly different sensor positions (spatial baseline) or times (temporal baseline) (Bamler & Hartl, 2020).
- Phase (φ) relates to path length (r) as:

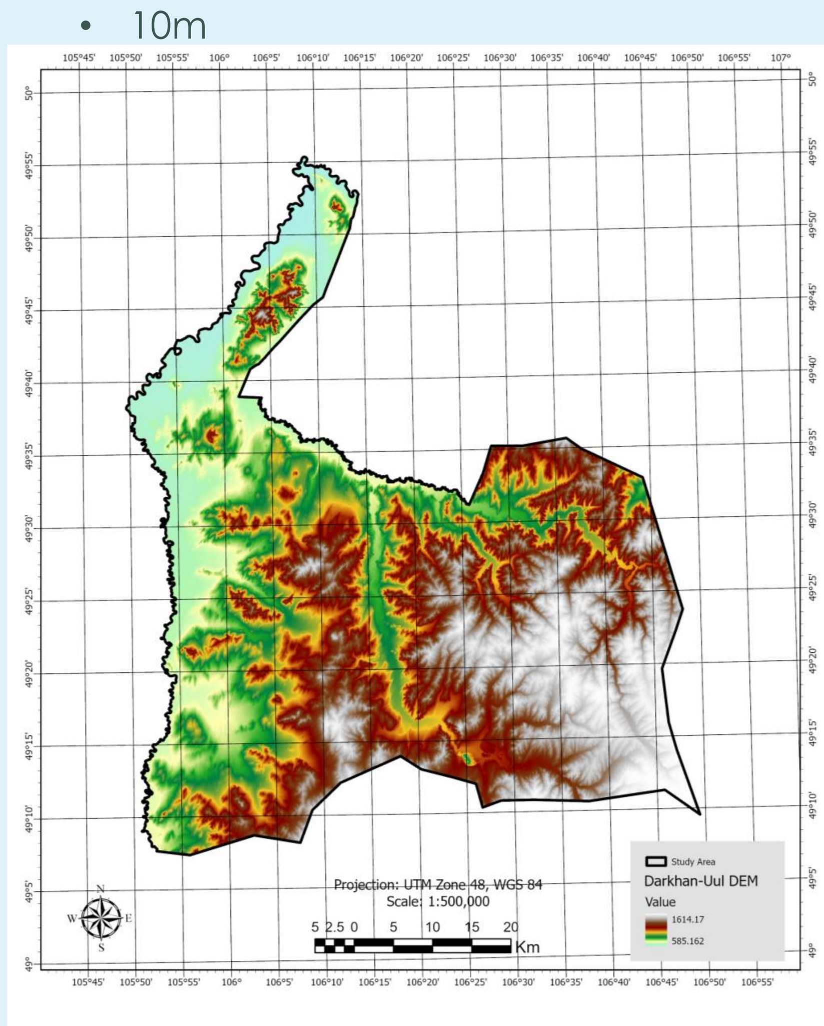
$$\varphi = (4\pi/\lambda)r \quad (1)$$

where λ is the radar wavelength (Hanssen, 2021).

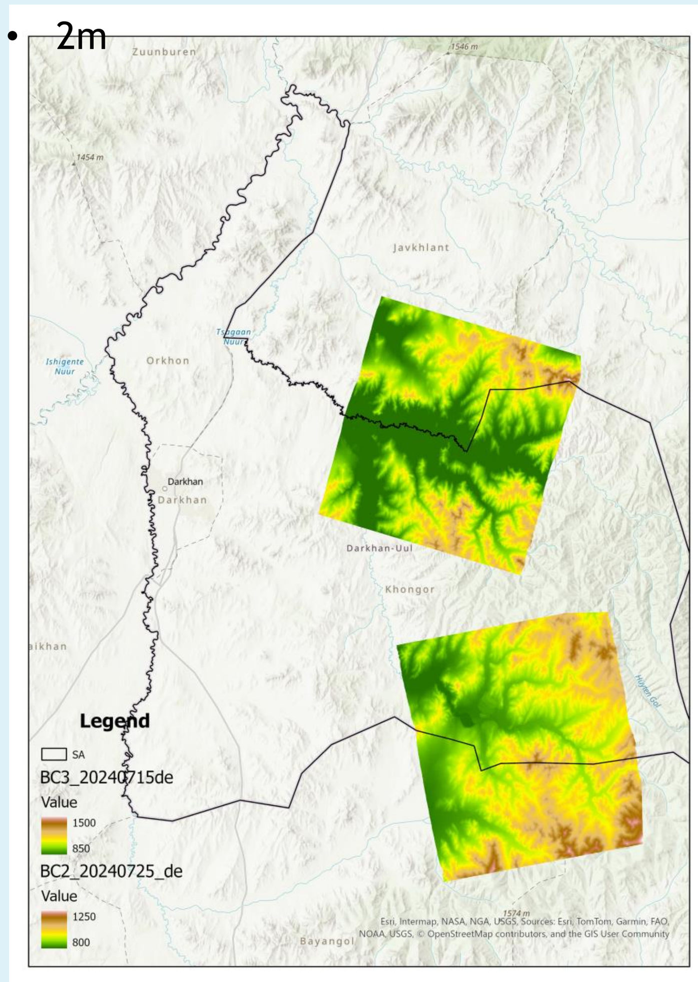


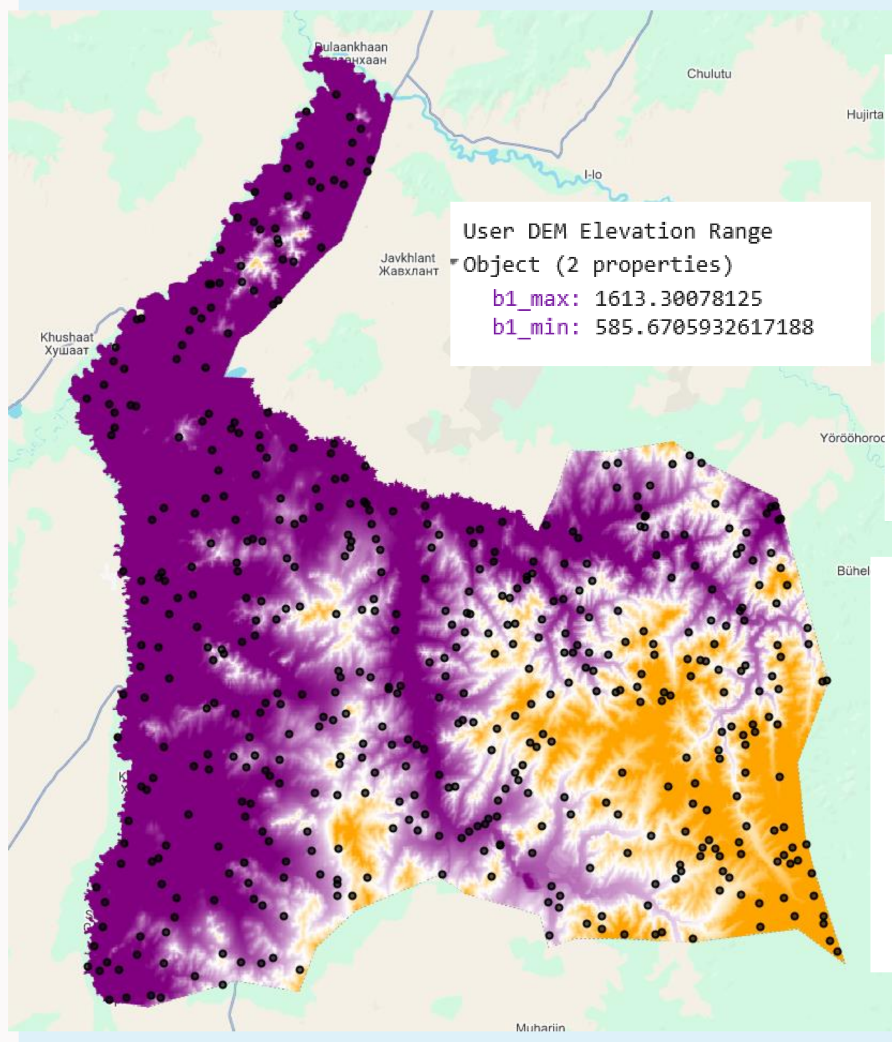
RESULTS AND ANALYSIS

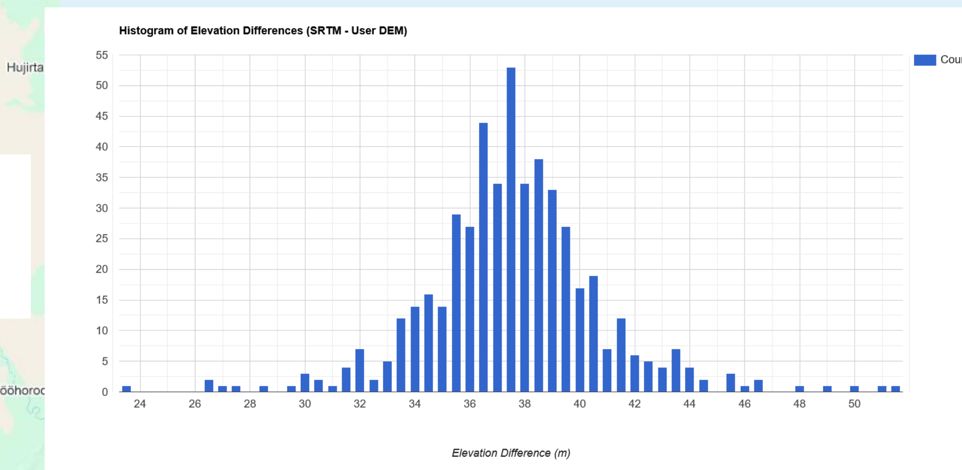
- DEM generated from Sentinel 1 data
  - 10m

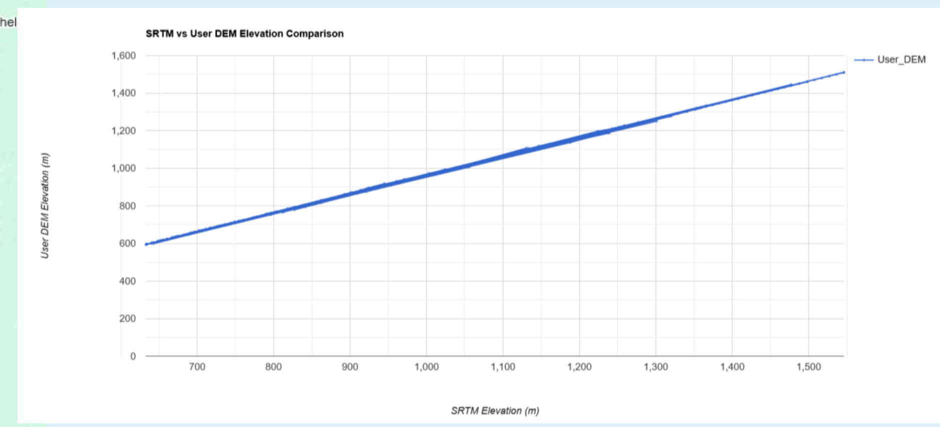


- DEM generated from SpaceTY MiniSAR data
  - 2m

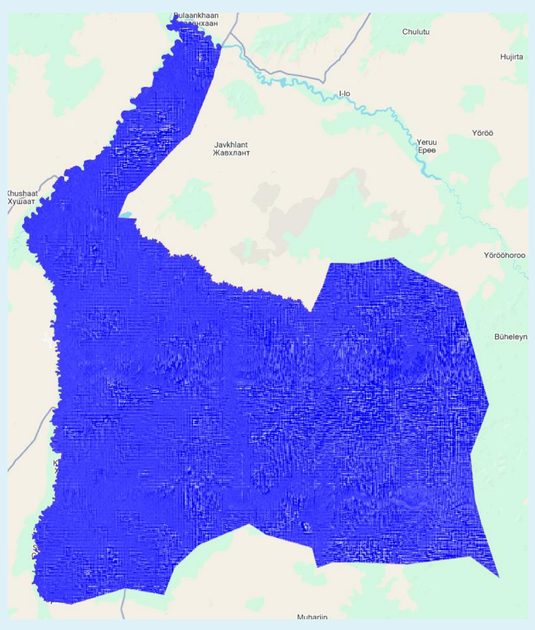








- Difference between DEM generated from Sentinel 1 data and SRTM DEM and ALOS



ALOS - User DEM Difference Stats
Object (4 properties)
max: 54.3544921875
mean: 39.36009265136719
min: 28.9947509765625
stdDev: 2.939769461025041

SRTM - User DEM Difference Stats
Object (4 properties)
max: 51.87841796875
mean: 37.83809265136719
min: 23.9947509765625
stdDev: 3.2404722413204423

RMSE ALOS vs SRTM
4.0627576841352475

RMSE ALOS vs User DEM
39.46972432141102

RMSE SRTM vs User DEM
37.97659694917669

ALOS vs User DEM Correlation
Object (2 properties)
correlation: 0.9998621298622277
p-value: 0

SRTM vs User DEM Correlation
Object (2 properties)
correlation: 0.9998267555769434
p-value: 0

CONCLUSION

1. Sentinel-1 InSAR can supplement global DEMs in low-vegetation areas but requires terrain-specific corrections.
2. For Mongolia's mixed landscapes, a fusion of ALOS (forests) + Sentinel-1 (steppe) + SRTM (baseline) is optimal.
3. InSAR processing improvements (e.g., PSI/SBAS) could enhance Sentinel-1 DEM accuracy.

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