# Single Comprehensive Digital Elevation Model for Sri Lanka: Modified Advanced Land Observing Satellite (ALOS) Radiometrically Terrain Corrected (RTC) Products

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**Abstract**: *Digital Elevation Models (DEMs) represent the earth's surface and topography, and high resolutions are essential for applications such as urban planning, flood risk management, forestry management, environmental monitoring and conservation, transportation infrastructure, and agriculture. Most freely accessible, direct-use DEMs such as Global DEM (GTOPO30), Shuttle Radar Topography Mission (SRTM) and Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) have lower spatial resolutions (>30 m). The Survey Department of Sri Lanka offers high-resolution DEMs with spatial resolution of 1 m, 2 m, and 5 m. However, these DEMs only cover ~75% of the country, while for the rest of the area, the SRTM 1 arc sec DEM (spatial resolution= 30 m) is the only available high-accuracy source. Hence, the current work focuses on a novel process and creating a seamless high-resolution DEM for all over Sri Lanka. The Advanced Land Observing Satellite (ALOS) Radiometrically Terrain Corrected (RTC) 12.5 m resolution DEM (2006-2009), was considered, and the data were modified as follows, the ALOS RTC DEMs are originally used ellipsoidal height (h), which needed to be converted to Orthometric height (H). The equation used was H = h – N, where N is geoid height. This conversion was conducted using ArcGIS software incorporating the Earth Gravitational Model (EGM96). The converted data was validated against the SRTM 1 arc sec DEM, LiDAR-derived DEMs and Photogrammetric Digital Data from the Survey Department of Sri Lanka, resulting in Root Mean Square Error (RMSE) of 4.2 m, 6.2 m, and 5.8 m respectively. This conversion and validation were carried out for the first time in Sri Lanka and showed promising results as a single DEM for the entire country with high accuracy. Furthermore, it is expected that a similar process can be applied to other countries, which needs to be further investigated.*

*Keywords: Digital Elevation Models, Spatial resolution, Sri Lanka*

## Introduction

Digital Elevation Model (DEM) is a digital representation of the Earth's surface providing basic information about the terrain relief (Mukherjee et al., 2013; Guth, 2006). DEM and its derivatives such as slope, aspect, drainage network, curvature and, topographic index are important parameters for information extraction or assessment of any process using terrain analysis (Mukherjee et al., 2013). Furthermore, DEMs are prerequisite in different applications such as hydrological modelling, route modelling, mass movement, landform analysis, creation of relief maps, terrain visualization and mapping, climate and meteorological studies. The outcomes of the aforementioned models depend on the accuracy of DEM (Mukherjee et al., 2013).

The current DEMs available for Sri Lanka suffer from insufficient spatial resolution. Since many critical applications such land planning, hydrology, disaster management, and infrastructure development are based on topographic data, a high resolution DEM is urgently needed to support these activities effectively. To achieve this goal, the present study focuses on developing a novel process to create a seamless high resolution DEM for the entire Sri Lanka. The Advanced Land Observing Satellite (ALOS) Radiometrically Terrain Corrected (RTC) DEM, with a 12.5 meters resolution, was selected for this purpose. The data were converted from ellipsoidal heights to orthometric heights using ArcGIS software, incorporating the Earth Gravitational Model (EGM96). The accuracy of the converted DEM was validated through Root Mean Square Error (RMSE) analysis.

## Literature Review

Earth's surface elevation measurements are very important in geographic applications. DEM is generated using different techniques such as photogrammetric method using stereo data (Mukherjee et al., 2013; San and Suzen, 2005; Hohle, 2009), interferometry (Mukherjee et al., 2013; Kervyn, 2001), airborne laser scanning (Mukherjee et al., 2013; Favey et al., 2003), aerial stereo photograph (Mukherjee et al., 2013) and topographic surveys using interpolation of contours maps (Mukherjee et al., 2013; Wilson and Gallant, 2000).

A DEM requires a coordinate system and a reference frame, with horizontal, vertical, and temporal components, which need to be specified in the metadata. Datums are defined at different scales (global, regional, national, or local) and timeframes, with each datum ideally assigned a unique European Petroleum Survey Group (EPSG) code. The horizontal datum, generally WGS84 or an equivalent, determines how the latitude and longitude coordinates map to the Earth's surface. The vertical datum defines the 0 elevation, and can be in terms of an ellipsoidal or geoidal (mean sea level) reference frame, which can differ by up to about 100 m.

Orthometric height (H) refers to the vertical distance from the reference geoid or mean sea level to a specific point on the Earth's surface. In contrast, ellipsoidal height (h) is the distance measured from a designated ellipsoid to that same point. The difference between these two heights is the geoid height (N), which represents the distance between the reference geoid and the designated ellipsoid (Figure 1). This value can be either positive or negative, with magnitudes potentially reaching up to around 100 meters.

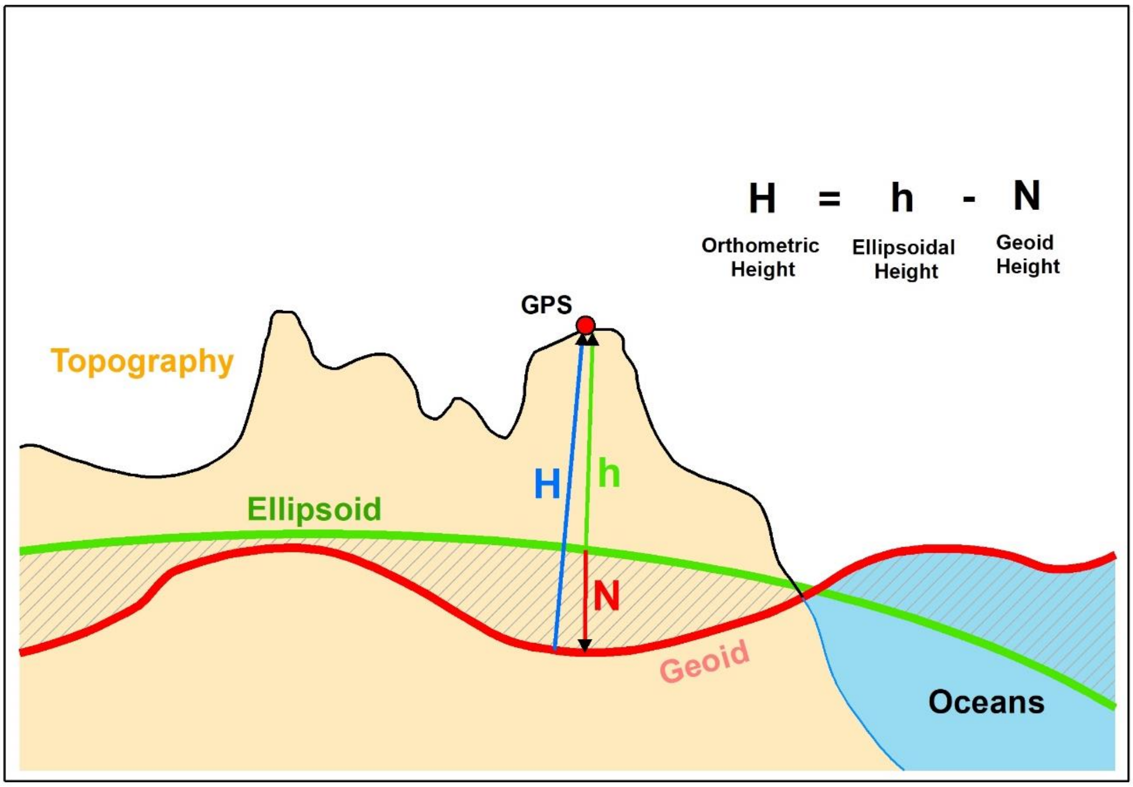


Figure 1: Illustration of the Earth's Surface Showing the Ellipsoid, Geoid, Orthometric Height, Ellipsoidal Height, and Geoid Height.

Geoidal datums can be global, such as EGM2008 (Guth et al., 2021; Pavlis et al., 2012), continental, national, or local. The temporal component reflects when the data were acquired, which can be almost instantaneous (e.g., the Shuttle Radar Topography Mission, SRTM, was collected in less than two weeks), or the collection can be over a significant period of time during which the Earth's surface could have changed. Over time, the land surface can change through natural or human activity and even plate tectonics, which creates measurable displacements (Guth et al., 2021).

A Digital Surface Model (DSM) represents a type of Digital Elevation Model (DEM) that captures the lower boundary of the atmosphere and intersects with other spheres such as the lithosphere, hydrosphere, cryosphere, biosphere, or anthroposphere. In contrast, a Digital Terrain Model (DTM) is a DEM that specifically records the boundary between the lithosphere and the atmosphere, excluding features from the biosphere and anthroposphere. This type of model is often referred to as a "bare-earth" DEM. It is important to specify the treatment of elements like the hydrosphere, cryosphere, and any voids such as buildings, water bodies, and trees by using localized masks to ensure accuracy (Guth et al**.,** 2021**).**

Small scale DEMs are essential for global and regional simulation studies, but their applicability largely depends on their vertical accuracy (Mukherjee et al., 2013; Dragut and Eisank, 2011). Numerous studies have been conducted to assess the vertical accuracy of DEMs (Mukherjee et al., 2013; Wu et al., 2008; Vaze et al., 2010; Zhou et al., 2012). However, there remains significant potential to further evaluate open source DEMs.

A geoid model is necessary to convert GPS derived ellipsoidal heights to orthometric heights, which are critical for applications like flood modelling, infrastructure development, and hydrological studies. Without a reliable geoid model, GPS data alone is often unsuitable for precise elevation mapping. GPS elevation measurements (orthometric heights) are inaccurate over Sri Lanka due to the unavailability of a proper geoid model. (Prasanna & Tantrigoda, 2009).

The large and rapidly varying geoid ellipsoid separation over Sri Lanka necessitates complex data reduction from terrestrial surveys to align with a geocentric datum for land surveyors (Abeyratne et al., 2010; Featherstone & Kuhn, 2006; Featherstone & Rueger, 2000). This complexity is due to significant geoid undulations that complicate the accurate transformation of elevation data.

Currently, orthometric heights are available at just over two hundred geodetic control stations distributed across the island. The geoid undulations relative to the WGS84 ellipsoid at these stations can be calculated using direct substitution methods (Prasanna & Tantrigoda, 2009).

Several DEM datasets are available for Sri Lanka, as summarized in Table 1. These include the Global Topographic Model (GTOPO30), which has a spatial resolution of 30 arc seconds (approximately 1 kilometer) and was generated in 1996, and the Shuttle Radar Topography Mission (SRTM) DEM, available in both 3 arc second (approximately 90 meters) and 1 arc second (approximately 30 meters) resolutions, generated in 2000. Additionally, the Global Multi resolution Terrain Elevation Data 2010 (GMTED2010) offers spatial resolutions of 7.5, 15, and 30 arc seconds.

Table 1: Freely available DEMs over Sri Lanka (ND – No Data).

| | **SRTM 3 arc seconds (void filled)** | **SRTM 1 arc seconds** | **GMTED2010** | **GTOPO30** |
|---|---|---|---|---|
| Spatial Resolution | 3 arc seconds (~90 meters) | 1 arc seconds (~30 meters) | 7.5, 15 and 30 arc seconds (~250, ~500, ~1000 meters) | 30 arc seconds (~1000 meters) |
| Acquisition Date | 11th Feb 2000 to 20th Feb 2000 | 11th Feb 2000 to 20th Feb 2000 | 11th Nov 2010 | 1st Dec 1996 |
| Geoid | EGM96 (Earth Gravitational Model 1996) | | | |
| Data Source | USGS EarthExplorer | | | |
| Accuracy (RMSE) | ND | ND | At 30 arc-seconds, RMSE range is 25 - 42 meters; at 15 arc-seconds, the RMSE range is 29 - 32 meters; and at 7.5 arc-seconds, the RMSE range is 26 - 30 meters. | ND |

While these DEMs provide useful elevation data, they are limited by relatively low spatial resolutions, which can impact the precision of geospatial analysis in applications requiring finer detail. The Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3 (ASTGTM) provides a global DEM of Earth's land areas at a spatial resolution of 1 arc second (approximately 30 meters horizontal posting at the equator), using the EGM96 geoid for vertical referencing. The data was acquired between March 1, 2000, and November 30, 2013 (NASA EarthData).

The Survey Department of Sri Lanka provides high resolution DEMs with spatial resolutions of 1 meter, 2 meters, and 5 meters. However, these high resolution DEMs are available only for specific areas, leaving gaps in the elevation data coverage across the entire country. In regions where high resolution DEMs are not available, the SRTM 30 meters DEM remains the primary high accuracy source. To address this issue, the current work focuses on developing a novel method to create a seamless, high resolution DEM for all of Sri Lanka. This effort utilizes the Advanced Land Observing Satellite (ALOS) Radiometrically Terrain Corrected (RTC) DEM with a resolution of 12.5 meters. This dataset, acquired between 2006 and 2009, offers more recent data compared to other sources such as SRTM, ASTER, and GTOPO30.

**Methodology**

The ALOS Radiometrically Terrain Corrected (RTC) data were downloaded from the Alaska Satellite Facility. The temporal extent of this data ranges from 2006 to 2009, with a spatial resolution of 12.5 meters. These are the most recent elevation data available.

First, an analysis was conducted to determine the need for correction and to quantify the errors observed in the original ALOS dataset when applied to Sri Lanka. Elevation values were extracted from both the ALOS RTC DEM and the SRTM 1 arc second DEM at evenly distributed points, spaced 1 kilometer apart. These data were then plotted against the sampling points to compare the ALOS RTC DEM elevations with the SRTM 1 arc second elevations.

Secondly, the following process for data correction was proposed and validated. The RTC products over Sri Lanka utilise the Projected Coordinate System: WGS 1984 UTM Zone 44N. The RTC DEMs are in ellipsoid height and SRTM 1 arc second DEM (30 meters) has been used for the RTC processing which utilize EGM96 datum.

Ellipsoidal height needs to be converted to the orthometric heights for many applications. In this research, ellipsoidal heights were converted to orthometric heights using a geoid correction approach, facilitated by ArcMap 10.8. The workflow involved creating a mosaic dataset and applying the Arithmetic function to adjust the elevation data based on the following equation:

$$H = h - N$$

Where,

h = ellipsoidal height

H = orthometric (geoid) height

N = geoidal separation

**a. Creation of a Mosaic Dataset:**

The process began by setting up a mosaic dataset using the Create Mosaic Dataset tool. Relevant elevation raster data representing ellipsoidal heights was then added to the mosaic dataset using the Add Rasters to Mosaic Dataset tool.

**b. Applying the Geoid Correction:**

To convert the ellipsoidal heights (h) to orthometric heights (H), the Arithmetic function was applied within the mosaic dataset. The function chain was modified in the following steps:

- ✓ Input Raster 1 was defined as the current mosaic dataset, representing the ellipsoidal heights (h).
- ✓ Input Raster 2 was specified as the geoid model (WGS84 geoid image, N), accessed from the ArcGIS installation folder.
- ✓ The Minus operation was selected in the Arithmetic function to subtract the geoidal separation (N) from the ellipsoidal heights (h) to compute the orthometric heights (H).

**c. Function Chain and Orthorectification:**

After the Arithmetic function was applied, the resulting mosaic dataset contained the orthometric heights. This dataset could then be used as a digital elevation model (DEM) for further geospatial analysis.

## d. Void fill

After the conversion, the resulting DEM was further examined for voids. Any identified voids were filled using the Elevation Void Fill function in ArcGIS software, ensuring a continuous and complete elevation model for further analysis.

## e. Validation of the Resulting DEM Using RMSE Calculation

The resulting DEM from the above conversion process was validated by comparing it with three reference datasets: the SRTM 1ArcSec DEM, photogrammetric digital data, and LiDAR-derived DEM. Validation was carried out using common sampling points across the datasets, as illustrated in Figure 2.

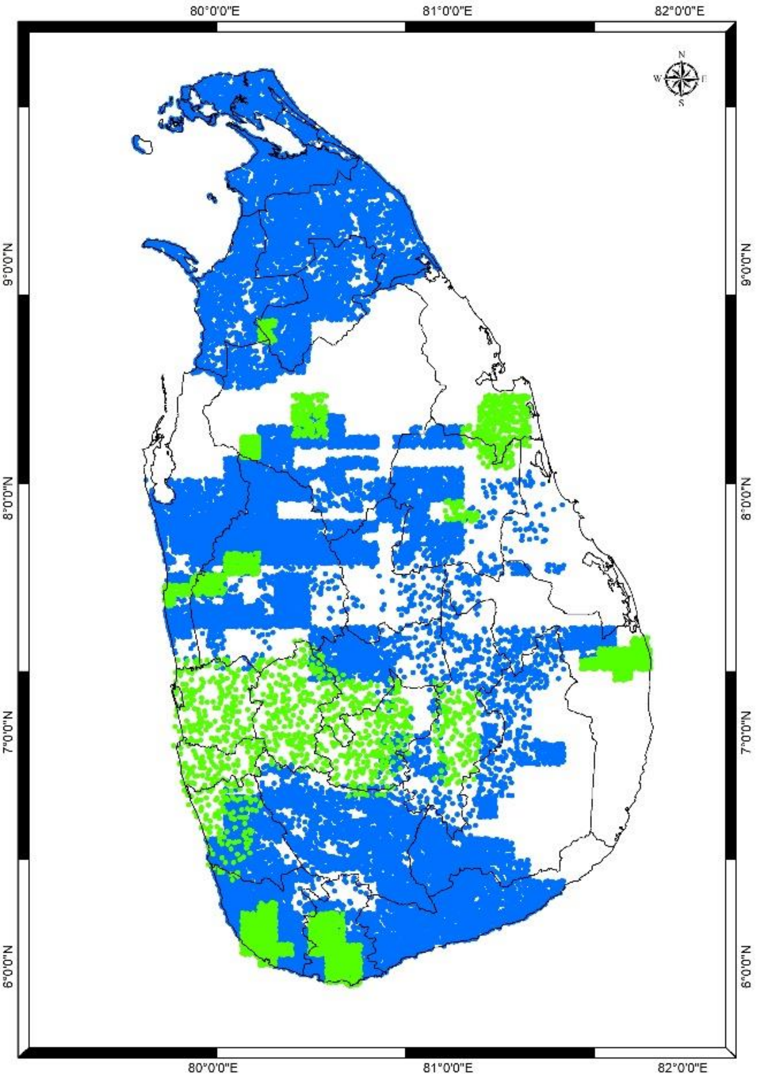


Figure 2: Map showing the distribution of sampling points, including SRTM 1 arc second DEM points (combined blue and green), photogrammetric digital data points (blue), and LiDAR derived DEM points (green).

To assess the accuracy of the result DEM, the Root Mean Square Error (RMSE) was calculated for each comparison. The RMSE values provided a quantitative measure of the elevation discrepancies between the result DEM and the reference datasets, thereby validating the accuracy of the conversion from ellipsoidal to orthometric heights.

The methodology followed in this study is summarized in Figure 3, which outlines the key steps involved. These include the creation of a mosaic dataset, applying geoid corrections, executing function chains for orthorectification, filling voids in the data, and validating the final DEM using RMSE calculations to ensure accuracy and consistency across the dataset.

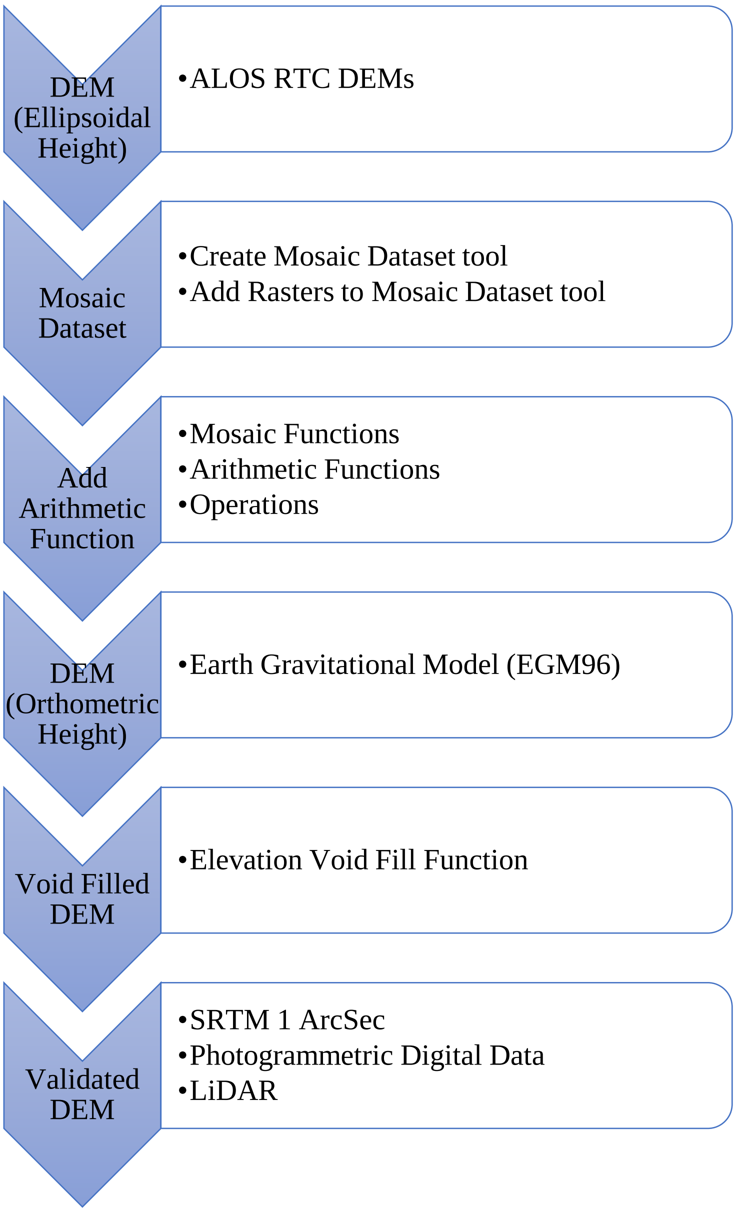


Figure 3: Workflow of the methodology, including mosaic dataset creation, geoid correction, function chain for orthorectification, void filling, and DEM validation using RMSE calculation.

## Results and Discussion

Suitability of directly applying the ALOS dataset to Sri Lanka was assessed by comparing approximately 5,000 data points from the ALOS DEM with SRTM data covering the entire country. Figure 4 illustrates this comparison, highlighting significant differences between the datasets.

Due to the undulating nature of the Earth's surface, the geoid, ellipsoid, and the physical Earth's surface do not coincide with one another (Prasanna and Tantrigoda, 2009; Knudsen and Anderson, 2013). In this study, we observed that the discrepancy between the global geoid model EGM96 and the WGS84 ellipsoid is negative, with a difference of approximately 97 meters. (Figure 4, 5 and 6) This variance highlights the necessity of applying geoid corrections when converting between orthometric and ellipsoidal heights, ensuring more accurate elevation measurements across varying terrain (Figure 4).

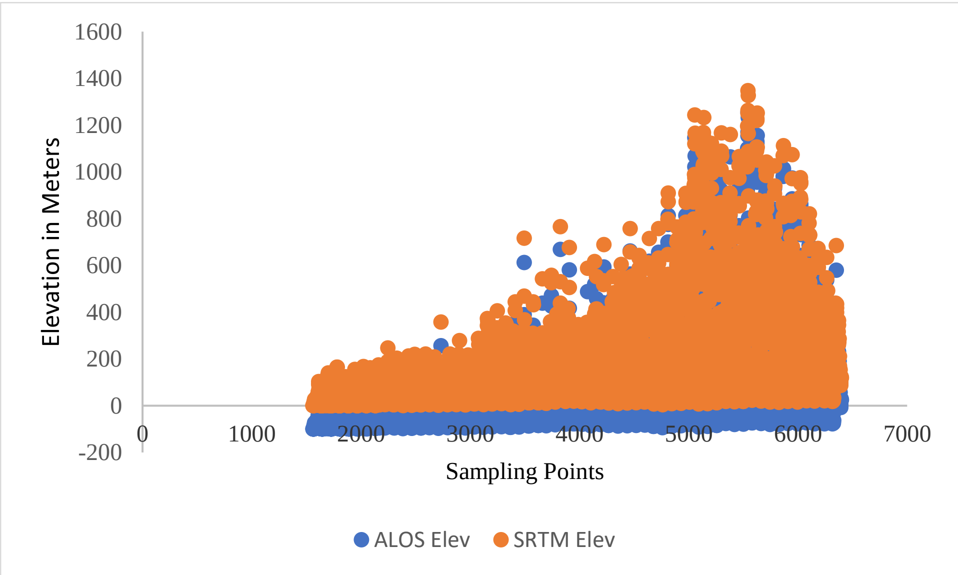


Figure 4: The graph of comparing ALOS RTC DEM elevations with SRTM 1-arc-second DEM elevations, plotted against the sampling points.

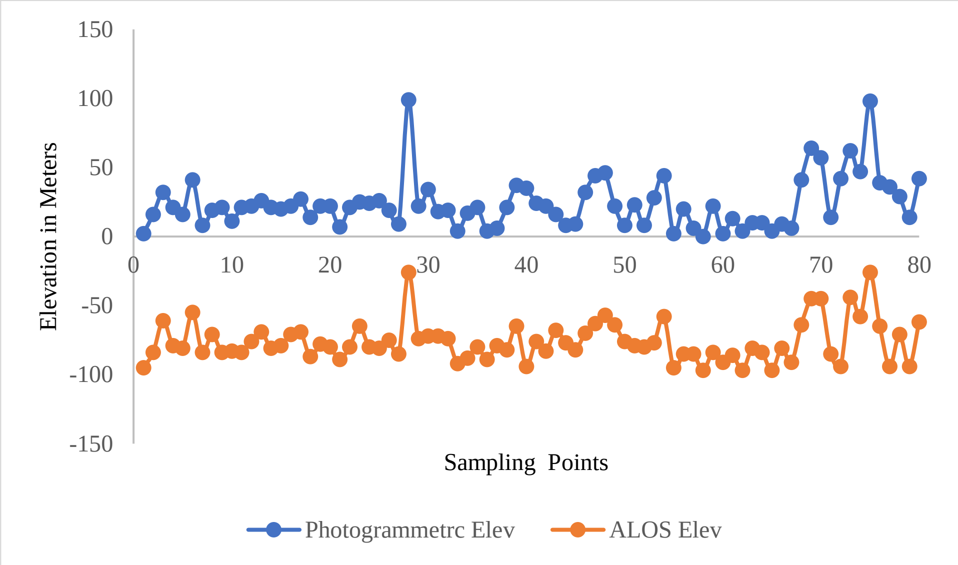


Figure 5: The graph of comparing photogrammetric digital elevation data with ALOS RTC DEM elevation data, plotted against the sampling points.

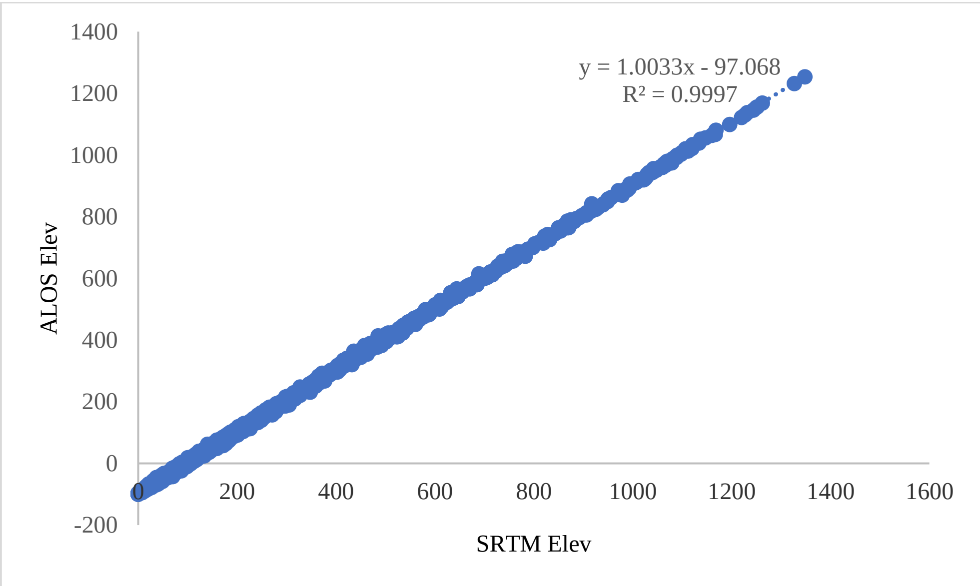


Figure 6: Plot that shows the correlation between SRTM DEM elevation and ALOS RTC DEM elevation.

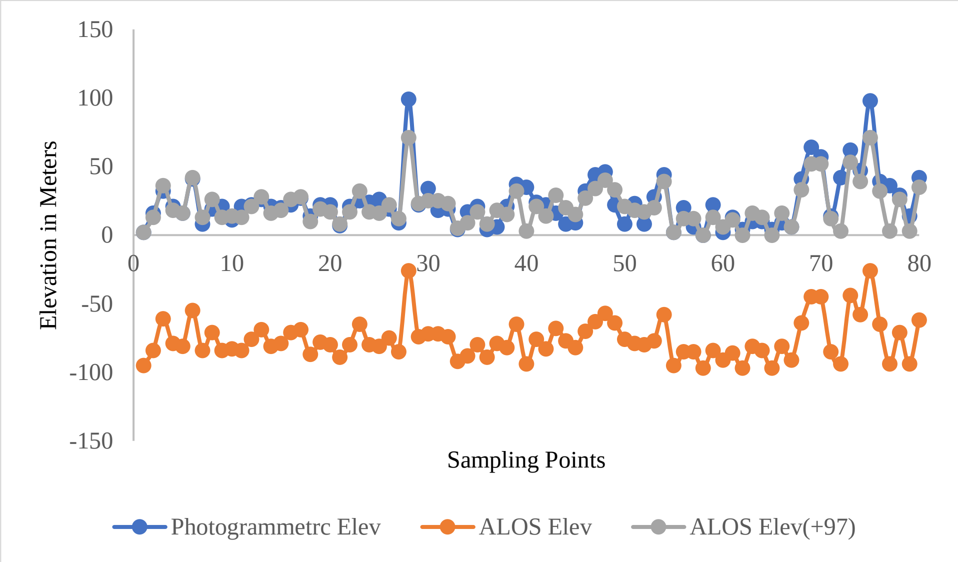


Figure 7: The graph of comparing photogrammetric digital elevation data, ALOS elevation data, and corrected ALOS data (adjusted by adding 97 to each point), plotted against the sampling points.

The ALOS RTC data were converted from ellipsoidal heights to orthometric heights using ArcGIS software, incorporating the Earth Gravitational Model (EGM96). Then the Photogrammetric digital elevation data, LiDAR Elevation and corrected DEM data, were extracted for the selected common points and plotted as shown in figure 8, Correction included was successful and approximately accurate data was observed.

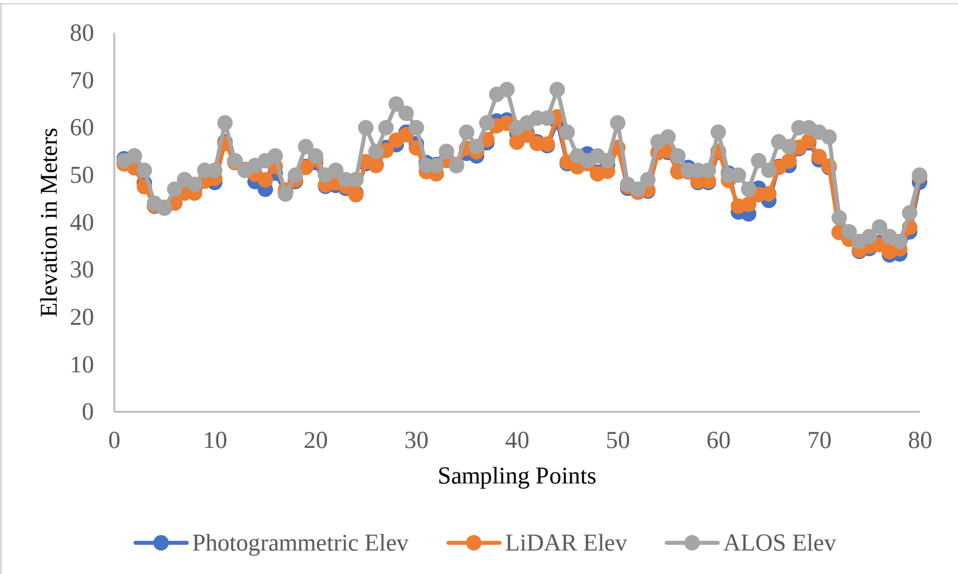


Figure 8: The comparison of Photogrammetric digital elevation data, LiDAR Elevation and corrected DEM data.

Following the conversion process, the resulting DEM was thoroughly inspected for any gaps or voids. In this study, the Elevation Void Fill function in ArcMap 10.8 was employed to address voids in the DEM. Voids, which occur when no points are collected for certain areas (often due to water bodies, class selection, or exclusions), were filled using a combination of plane fitting and Inverse Distance Weighted (IDW) algorithms. The initial step used a basic method, averaging the values of eight neighbouring pixels to fill smaller voids. The processed DEM was mapped as shown in the figure 9.

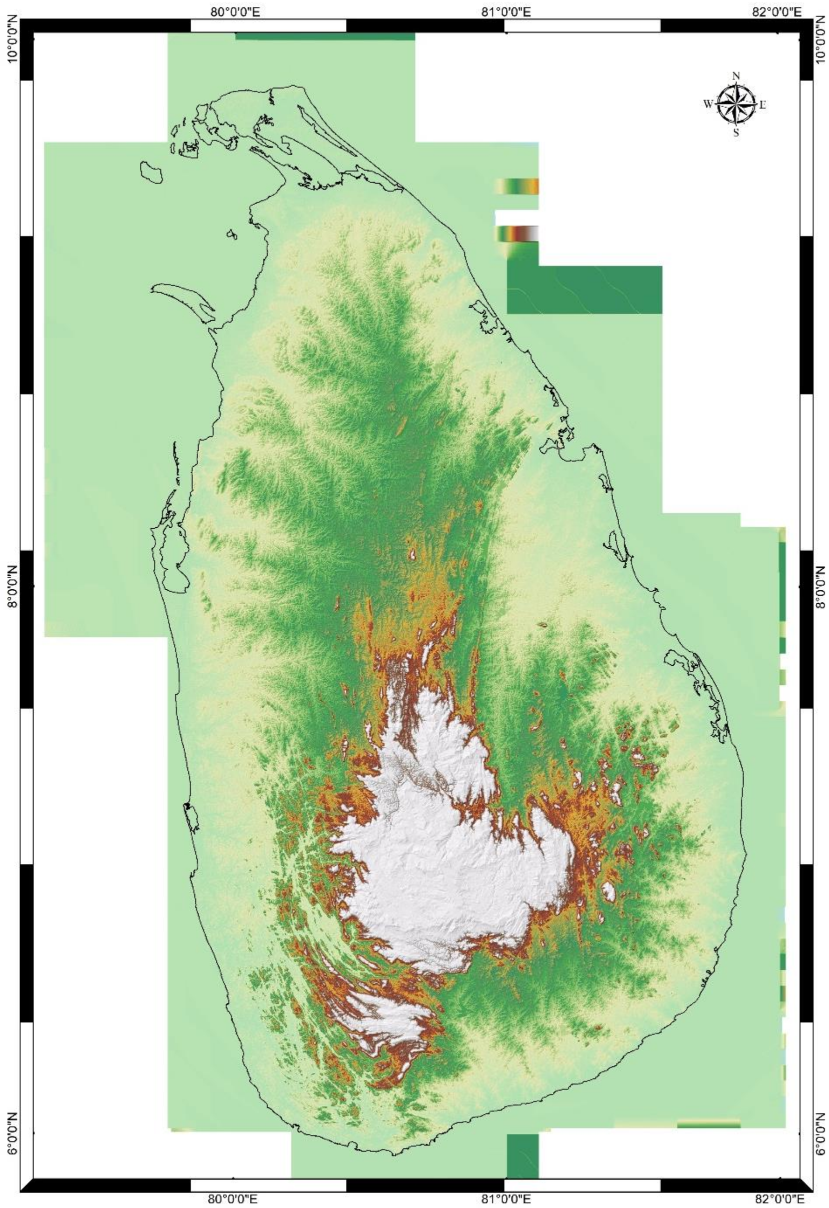


Figure 9: The map of Sri Lanka according to the obtained information from the processed ALOS RTC DEM showing the topography.

The converted data were validated against the SRTM 1 arc second DEM, LiDAR derived DEMs, and photogrammetric digital data from the Survey Department of Sri Lanka, resulting in Root Mean Square Errors (RMSE) of 4.2 meters, 6.2 meters, and 5.8 meters, respectively (Table 2). A total of 50,000 sample points were used for the comparison, except for LiDAR, which involved approximately 5,000 sample points. While the Survey Department data are highly accurate, they are limited in coverage across Sri Lanka. Notably, the corrected DEM offers similar accuracy to the Survey Department data, with a ±6 meters error margin, while providing comprehensive coverage across the entire country.

Table 2: Comparison of the Root Mean Squire Error which represents accuracy of the suggested DEM compared to the SRTM 1 arc second DEM, LiDAR derived DEMs and Photogrammetric Digital Data.

| | **SRTM 1 Arc Sec DEM** | **LiDAR-derived DEMs** | **Photogrammetric Digital Data** |
|---|---|---|---|
| Number of Sample points (approximately) | 50,000 | 5,000 | 50,000 |
| RMSE of Processed ALOS RTC DEM (meters) | 4.2 | 6.2 | 5.8 |

The Survey Department data is the highest resolution dataset available in Sri Lanka. However, it covers only about 75% of the country. Considering the resolution and coverage of all available DEMs for Sri Lanka, they can be ranked as follows: ALOS RTC Corrected > SRTM 1 arc second > SRTM 3 arc second. Since the current DEM enhances the accuracy of the high resolution ALOS RTC Corrected DEM, it is notable that the corrected DEM provides comprehensive coverage over Sri Lanka with both high resolution and accuracy.

Similar methodologies can be applied to suitable datasets in other countries facing similar issues with low coverage and less accurate DEMs. Further studies are needed to explore and validate these approaches in different regions.

## Conclusion and Recommendation

Sri Lanka requires more accurate methods for topographic mapping which provides full coverage. Compared to the Survey Department data and SRTM 1 arc second DEM, the ALOS RTC DEM needed correction for use in Sri Lanka. An initial simple correction to the ALOS RTC DEM using a +97 adjustment did not fully resolve the discrepancies. Subsequently, a conversion using the EGM96 geoid model was applied, resulting in a promising DEM where was validated against SRTM 1 arc second, LiDAR, and photogrammetric digital data, with Root Mean Square Errors (RMSE) of 4.2 meters, 6.2 meters, and 5.8 meters, respectively.

Since the current DEM is based on the high resolution ALOS RTC data, shows a low RMSE compared to the Survey Department data, and provides full coverage of Sri Lanka, it is recommended that the current DEM is a promising candidate as topographic information assessing tool to be used in Sri Lanka. Further studies with other countries or geographical locations are worthy of studying as well.

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