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Evaluation of CartoDEM with the Ice, Cloud, and Land Elevation Satellite-2 and Global Ecosystem Dynamics Investigation Spaceborne LiDAR Datasets for Parts of Plain Region in Moga District, Punjab †

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Abstract: The CartoDEM Version 3 Release 1 openly accessible datasets are currently the most reliable datasets for relatively plain regions in India specifically. The aim of the presented study is to evaluate CartoDEM with respect to two openly accessible spaceborne LiDAR datasets from two LiDAR sensors: the Advanced Topographic Laser Altimeter System (ATLAS) on board the Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) and Global Ecosystem Dynamics Investigation (GEDI) over the International Space Station (ISS). The differences and deviations were computed for CartoDEM and LiDAR footprint elevations for the two datasets, namely, ICESat-2 and GEDI. The difference values were filtered for footprints with differences between 0 and 2.5 in the DEM and LiDAR elevation values. Besides this, an overall estimate was also calculated for the elevation values obtained over the surface, i.e., the ground, as well as objects such as the trees or buildings. The RMSEs were observed to be 1.16 m and 1.74 m for the ICESat-2 and GEDI datasets for the points/footprints on the terrain, whereas when considering similar parameters for the two datasets, the RMSEs were found to be 1.78 m and 5.48 m for the ICESat-2 and GEDI footprints on the surface (terrain/object), respectively. This study reveals that CartoDEM is highly accurate in the plain regions when validated with respect to the ICESat-2 datasets, which work via the photon counting technique. Further, it was observed that ICESat-2's performance is better than that of the GEDI mission for terrain height. Thus, it was observed that the spaceborne LiDAR datasets from ICESat-2 can be utilized for the validation of DEMs and can be useful for applications where an input to a DEM is required for engineering or modeling applications.

Keywords: RS&GIS; DGPS; GCPL; Cartosat-1; satellite triangulation

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1. Introduction

A Digital Elevation Model (DEM) is commonly defined as "a digital representation of the terrain". DEMs are currently being prepared and are available for Earth and other celestial bodies, like the Moon and Mars, so a wider set of definitions is required. Thus a DEM is now aptly defined as "a digital representation of elevations (or height) of a topographic surface in form of a geo-rectified point-based or area-based grid, covering the Earth or other solid celestial bodies" [1]. DEMs express topographic information digitally, providing a convenient means for terrain analysis and visualization, as well as an input to models used in scientific analyses or predictions, which can be further improved by DEM fusion [2–4]. Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) datasets are also being used for the improvement of DEMs as well as the simulation of DEM using machine learning techniques [5,6].

Studies have found that the accuracy of terrain height data obtained from Global Ecosystem Dynamics Investigation (GEDI), available from the International Space Station (ISS), is lower than that of the Advanced Topographic Laser Altimeter System (ATLAS) sensor on the ICESat-2 satellite. However, GEDI has the advantage of more intensive spatial sampling, useful for the estimations of tree canopies and biomass [7]. Techniques like Random Sample Consensus (RANSAC) are used for fitting a model to experimental scientific input datasets while smoothing it [8,9] for remote sensing and photogrammetric solutions. The Constraint Analysis and Monitoring System (CAMS) utilizes a sophisticated set of algorithms to model and predict the position (location) and attitude (pointing) of the ICESat-2 instrument, providing highly accurate position information. The four major operational components are the Attitude Predictor and Event Scheduler (APES), Long-Term Orbit Predictor (LTOP), Two-Line Element (TLE) Propagator (TLEP), and Constraint Monitor (CM) [10]. These openly available global datasets have opened a gateway for research communities to utilize these in their domains. The current study compares and evaluates CartoDEM V3 R1 (henceforth referred as CartoDEM) elevation values with the terrain height data provided by ICESat-2 and GEDI.

2. Materials and Study Area

Openly accessible datasets, namely, the CartoDEM, ICESat-2, and GEDI datasets, were used in this study. The study area selected was the relatively plain region around Moga District, Punjab, as GEDI has multiple passes in this region (Figure 1a with beam names and Figure 1c under surface category), providing a good set of data for the purpose of this study, with the beams shown in Figure 1b.

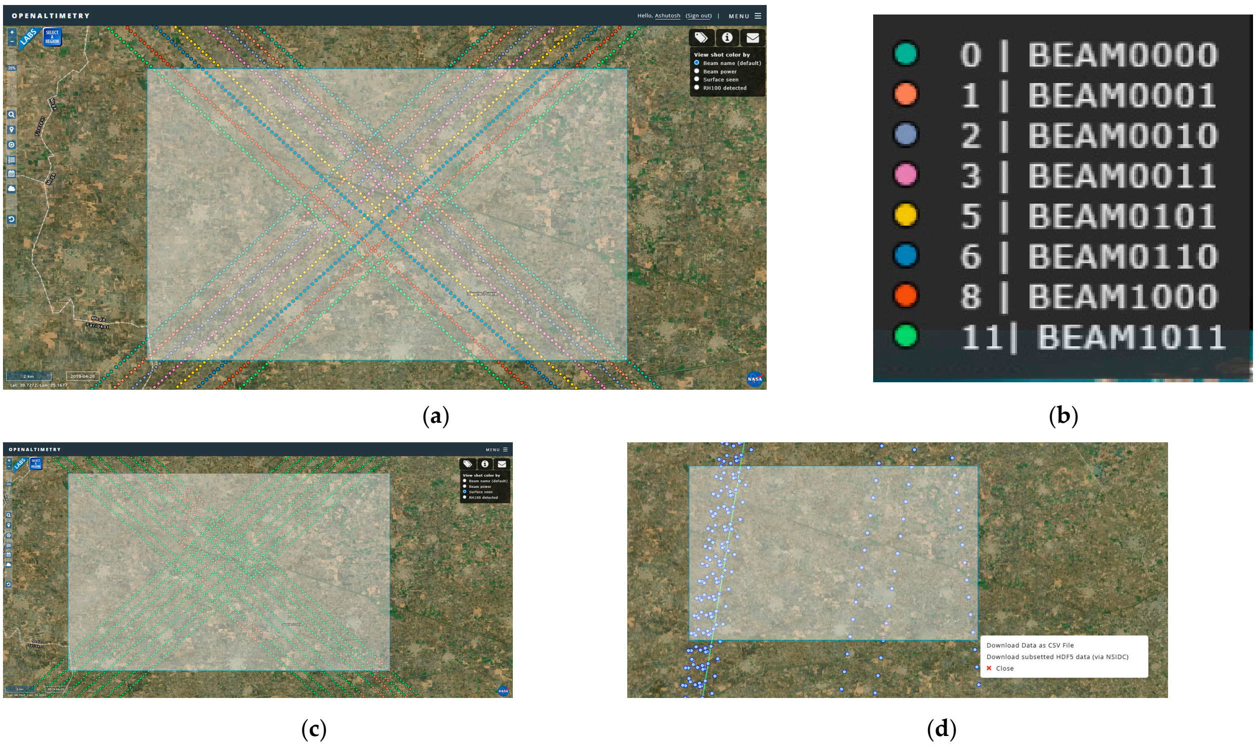

Figure 1. Footprints of the laser from the two sensors: (**a**) GEDI Beams over Moga region; (**b**) beam names/types; (**c**) GEDI footprints over parts of Moga district; (**d**) ICESat-2 footprints over parts of Moga district.

2.1. CartoDEM

CartoDEM Version 3 Release 1 is an improved DEM generated from the Cartosat-1 stereo datasets utilizing ground control points (GCPs) from the GCP Library (GCPL) for satellite triangulation [11,12], as well as corrections for waterbodies [13]. CartoDEM was downloaded from the Bhuvan web portal (Open data archive) of the National Remote Sensing Centre [14]. CartoDEM V3 R1 is the most dependable openly accessible DEM, since it is corrected through manual interventions, after the automatically generated DEM.

2.2. ICESat-2

ICESat-2 with an Advanced Topographic Laser Altimeter System (ATLAS) instrument was launched by NASA and measures the elevation of Earth's surface using a laser wavelength of 532 nm and a PRF of 10 kHz, producing a ~70 cm footprint on the ground. This ATL08 dataset provides geolocated land-ice surface heights (WGS 84, ITRF2014), plus ancillary parameters on the quality of the height estimates in the form of terrain uncertainty, which can be used to interpret or filter the values as per the application requirements. Figure 1d showcases the footprints of one of the passes over the study area [15].

2.3. GEDI

GEDI is deployed on the Japanese Experiment Module Exposed Facility (JEM-EF), and uses 1064 nm pulses at 242 Hz. GEDI produces high-resolution laser ranging observations of the 3D structure of the Earth, including forest canopy height, canopy vertical structure, and surface elevation, to characterize carbon and water cycling processes, biodiversity, and habitats. It consists of 3 lasers, among which two are full-power and one is split into two, producing a total of 8 beam transects on the ground. This results in about 25 m to 30 m footprint samples spaced approximately every 60 m along the track. The GEDI beam transects are spaced about 600 m apart on the ground with the use of Beam Dithering Units (BDUs) in the cross-track direction, for an overall across-track width of ~4.2 km (km) [16,17].

3. Methodology

Figure 2 provides the methodology used for the comparison and evaluation of the openly accessible datasets with the validation of CartoDEM with the ICESat-2 ATL08 dataset. The deviations were computed between the elevation values of CartoDEM and the two LiDAR datasets, namely, ICESat-2 and GEDI, at the footprint locations. Thereafter, the difference values were filtered for footprints with differences between 0 and 2.5 in the DEM and LiDAR elevation values to include hanging points above the DEM, while excluding objects like single- or multiple-story buildings. The ICESat-2 and GEDI footprints were overlaid on the CartoDEM V3 R1 dataset, as shown in Figure 3, for visualization. Besides this, an overall estimate is also calculated for the elevation values obtained over the surface, i.e., the ground, as well as objects such as the trees or buildings.

The root-mean-square errors (RMSEs) were calculated using Equations (1) and (2), respectively, for ICESat-2 and GEDI, to assess the variability among the elevation values. Additionally, the method of vertical accuracy assessment for the DEMs was detailed in terms of the linear error at the 90th percentile (LE90, 90% confidence) and was used extensively for accuracy assessments of the DEMs (Equation (3)) [18–20]. The mean error (ME) and mean absolute error (MAE) were also estimated for the assessment of overestimations and underestimations in the sampled footprint locations. The mean absolute deviation (MAD) was computed to assess the dispersion or variability in the ICESat-2 and GEDI datasets. MAD was computed using the average absolute difference between each data point and the mean of the dataset. Chi et al. (2014) and Willmott et al. (2005) discussed the pros and cons of MAE- and RMSE-based statistics, which is essential in the interpretations of datasets when constructing inferences [21,22].

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{i(\mathrm{CartoDEM})} - Z_{i(\mathrm{ICESat-2})}\right)^{2}}{n}} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{i(\text{CartoDEM})} - Z_{i(\text{GEDI})}\right)^2}{n}} \tag{2}$$

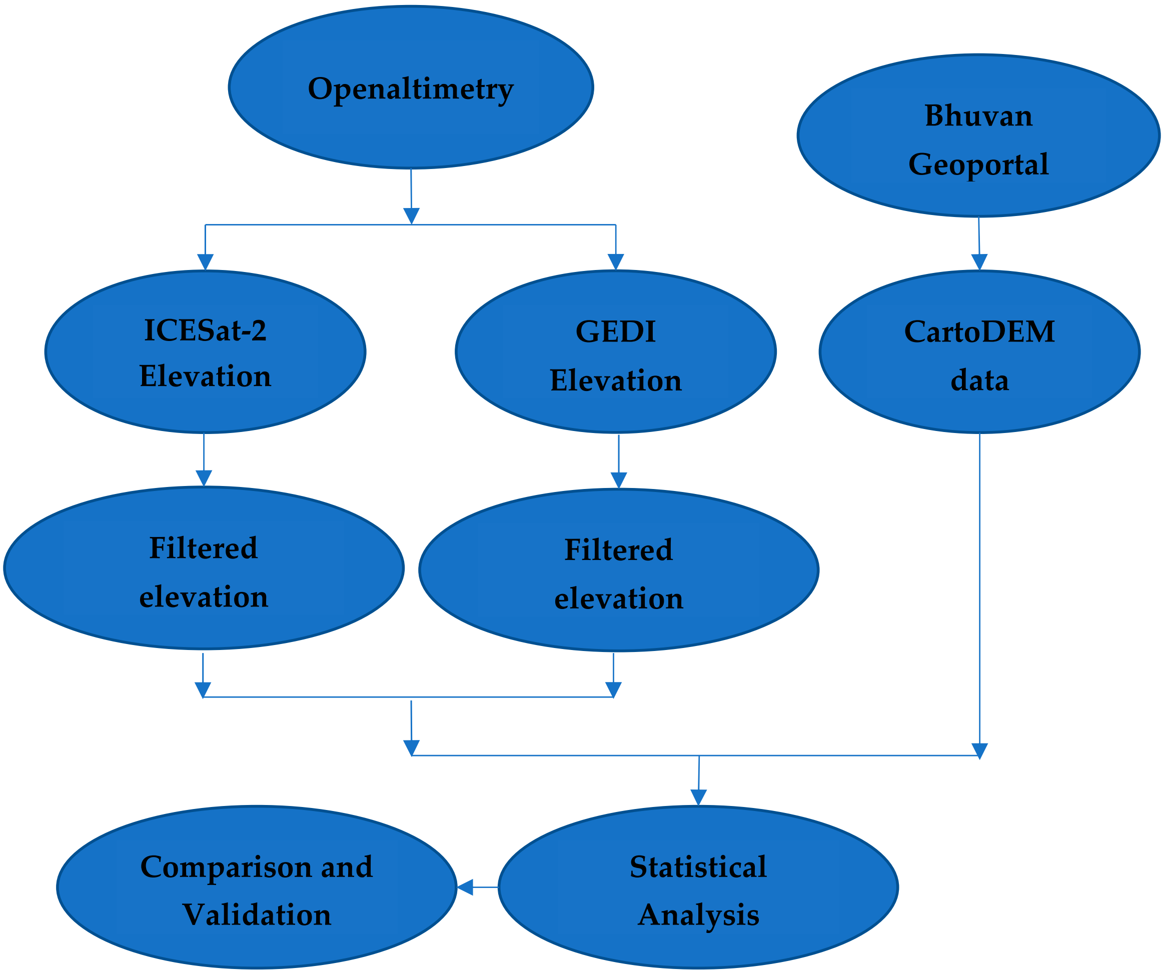

Figure 2. Flowchart for evaluation of CartoDEM with ICESat-2 and GEDI spaceborne lidar datasets for parts of plain region in Moga district, Punjab.

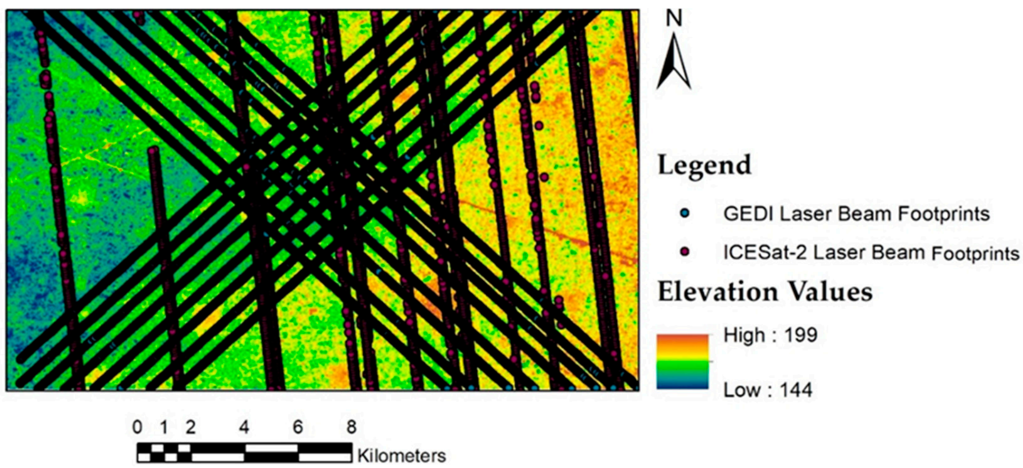

Figure 3. ICESat-2 and GEDI footprint locations overlaid on CartoDEM Version 3 Release 1 dataset of Moga region in Punjab.

In the above equations, $Z_{i(CartoDEM)}$ is the extracted elevation from the CartoDEM products at the ICESAT-2/GEDI footprint locations, $Z_{i(GEDI)}$ is the extracted elevation from the GEDI product, and $Z_{i(ICESat\text{-}2)}$ is the observed reference elevation with i = 1 to n, where n indicates the number of observations available for the comparison and/or validation.

$$LE90 = 1.6449 * RMSE \quad (3)$$

4. Results and Discussion

Figure 3 depicts the ICESat-2 and GEDI footprint locations overlaid on the CartoDEM Version 3 Release 1 dataset of the Moga region in Punjab. The RMSE is observed to be 1.16 m from the filtered 2802 footprints and 1.74 m from the filtered 367 footprints for the ICESat-2 and GEDI datasets for the locations of the footprints on the terrain, as shown in Table 1, considering deviations of less than 2.5 m (Table 1). On the other hand, considering values deviations of about 10 m, for the two datasets, the RMSE is found to be 1.78 m from the filtered 5203 footprints and 5.48 m from the filtered 4882 footprints for the ICESat-2 and GEDI footprints on the surface (terrain/object), respectively. MAD in Table 1 depicts that the filtered samples at difference values of 2.5 m have dispersion or variability in the ICESat-2 and GEDI datasets, indicating a better method for the assessment of CartoDEM accuracy. This study shows that through proper selection or filtering, the ICESat-2 datasets can be suitably used for applications requiring digital terrain models (DTM), digital surface models (DSM), and normalized digital surface models (nDSM) considering the study areas and the footprint sizes. nDSM can be obtained through the subtraction of DSM and DTM for specific applications, providing object (trees, buildings, etc.) heights [23]. The results achieved in our study are very close to those which are achieved by Pronk et al. (2023) in their latest study. Pronk et al. (2023) also showed that for all areas and land cover classes combined, ICESat-2 achieved a bias of −0.06 m, an MAE of 0.46 m, and an RMSE of 1.39 m, whereas GEDI was observed to be less accurate, with a bias of 0.45 m, an MAE of 0.98 m, and an RMSE of 5.66 m [24]. A difference of ±0.5 m can also be used for filtering for more stringent studies, depending on the application.

Table 1. ME, MAE, MAD, RMSE, and LE90 values of on-ground (considered suitable for DTM) and on-surface (considered suitable for DSM) application suitability for the two LiDAR datasets.

Datasets	DTM/DSM Applications	No. of Footprints	ME (m)	MAE (m)	MAD (m)	RMSE (m)	LE90 (m)
ICESat-2	DTM (on ground)	2802	0.94	0.94	0.57	1.16	1.91
	DSM (on surface)	5203	−0.06	1.31	1.31	1.78	2.93
GEDI	DTM (on ground)	367	1.62	1.62	0.53	1.74	2.86
	DSM (on surface)	4882	5.15	5.15	1.47	5.48	9.01

It is observed from Table 1 that as the filtering conditions are made more stringent for the ICESat-2 datasets, the filtered values depict only overestimations of the elevation values in CartoDEM, as only equal positive values remain for ME and MAE. Equal values for ME and MAE, in both cases of GEDI datasets, indicate that as per the filtered parameters, only overestimations are available in CartoDEM in the sampled locations. The ICESat-2 platform at a higher altitude is more stable than GEDI over ISS, thus providing better pointing as well as accuracy for terrain height measurements. The ME of −0.06 m for 5203 footprints also provides a reasonable indication of the good quality of the filtered samples of the ICESat-2 dataset.

5. Conclusions

This study focused on an evaluation of the quality of elevation products derived from two sensors, GEDI and ATLAS. The study concluded that the ICESat-2 datasets are relatively closer to the CartoDEM V3 R1 elevation values compared to the GEDI dataset, primarily emphasizing the more stable orbital dynamics of ICESat-2 compared to GEDI on the ISS platform. Further, the availability of a large number of high-quality filtered elevation values qualify the filtered ICESat-2 data for the validation of DEMs, such as CartoDEM in the presented study, for regions that have a plain topography. The mean absolute deviation (MAD) and mean error (ME) are able to quantify the dispersion or variability and bias, respectively, for the filtered sample datasets of ICESat-2 and GEDI, confirming the superiority of the ICESat-2 datasets over the GEDI datasets. This study also quantifies the expected accuracy that can be achieved from GEDI over a plain area, which is important for its utilization in any project work or the development of similar sensors for manned stations. Manned stations follow different orbital dynamics; for example, the Russian Progress Spacecraft is used for orbit-raising maneuvers for the ISS, which loses about two kilometers every month.

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