



Accuracy assessment of the CARTOSAT DEM using robust statistical measures

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Abstract

CARTOSAT-1-derived 10 m spatial resolution digital elevation model (DEM) for entire India was compiled for several applications. Overall assessment of the accuracy of this product requires additional regional studies involving ground truth control points and accuracy verification methods with a higher level of precision, such as the global positioning system (GPS). The study presented in this paper compares the accuracy of CARTOSAT-1 datasets with respect to eight sites over different terrains in India with the same GPS system. Robust statistical analysis including mean errors, standard deviation error, root mean square error (RMSE), skewness, kurtosis measures and Shapiro–Wilk’s normality test were used for evaluating error. The results of this study show a linear trend between the DEM and the ground control points (GCP). The mean error is very high in highlands ranging up to – 14.06 m, whereas in moderate terrain it ranges around 2.65 m and in the lowland about 1.20 m. RMSE ranges up to 28.82 m in rugged high-altitude topographies, 6.24 m in moderate and 1.98 m in low-altitude regions. However, this study shows that CARTODEM is one of the finest DEM that can be used for the Indian subcontinent as it works more accurately over plain and moderately undulating lands.

Keywords CARTOSAT1 · GPS · GCP · Statistics

Introduction

Digital elevation model (DEM) represents the relief of the Earth surface in digital format at regularly spaced horizontal intervals, and is prerequisite for any geometric, radiometric and atmospheric corrections of optical instruments (Toutin 2008). DEMs represent the relationship between different components of the land surface (Hu et al. 2009), and since a long time they have been highly useful in landform analysis (Weibel and Heller 1990), creation of relief maps (Fraser et al. 2002), terrain visualization and mapping (Spark and Williams 1996), volcanic hazards (Vassilopoulou et al. 2002), application of water flow (Jain and Singh 2003), estimating runoff (Cai and Wang 2006; Chappell et al. 2006),

flood simulation and management (Qi and Altinakar 2011; Ramlal and Baban 2008), route modelling (Romanowicz et al. 2008), mass movement (Iwahashi et al. 2003), climate and meteorological studies (Tarboton 1997). Increase in applications of DEM has gradually increased the demand of higher spatial resolution of DEMs with higher accuracy, so that these can be used in advanced application of remote sensing and geographical information system (GIS)-induced studies (Deilami et al. 2012). DEMs are normally made by using four steps such as data acquisition by the sensors, resampling to grid spacing, interpolation to extract height of point and final elevation representation in the form of DEM. These basic steps are used in different techniques of gathering information such as topographic surveys (Wilson and Gallant 2000), aerial stereo photograph (Schenk 1996), interferometry (Kervyn 2001), photogrammetric method using stereo data (San and Suzen 2005) and airborne laser scanning (Favey et al. 1999) to represent elevation details. Error can appear in any of these steps for generating the resulting DEM which may be systematic or random (Holmes et al. 2000; Li et al. 2006; Fisher and Tate 2006; Rodriguez et al. 2006; Mukherjee et al. 2013). It is essential thus to evaluate the accuracy of DEMs generated from

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satellite images, since the accuracy of the resulting DEM also impacts the accuracy and reliability of the conducted analysis; thus, several researches have been conducted in recent years on the accuracy of DEMs generated from optical and radar data (Toutin 2002, 2004; Cuartero et al. 2005; De Oliveira and Paradella 2008; Peng et al. 2005; Chen et al. 2007; Mukherjee et al. 2015).

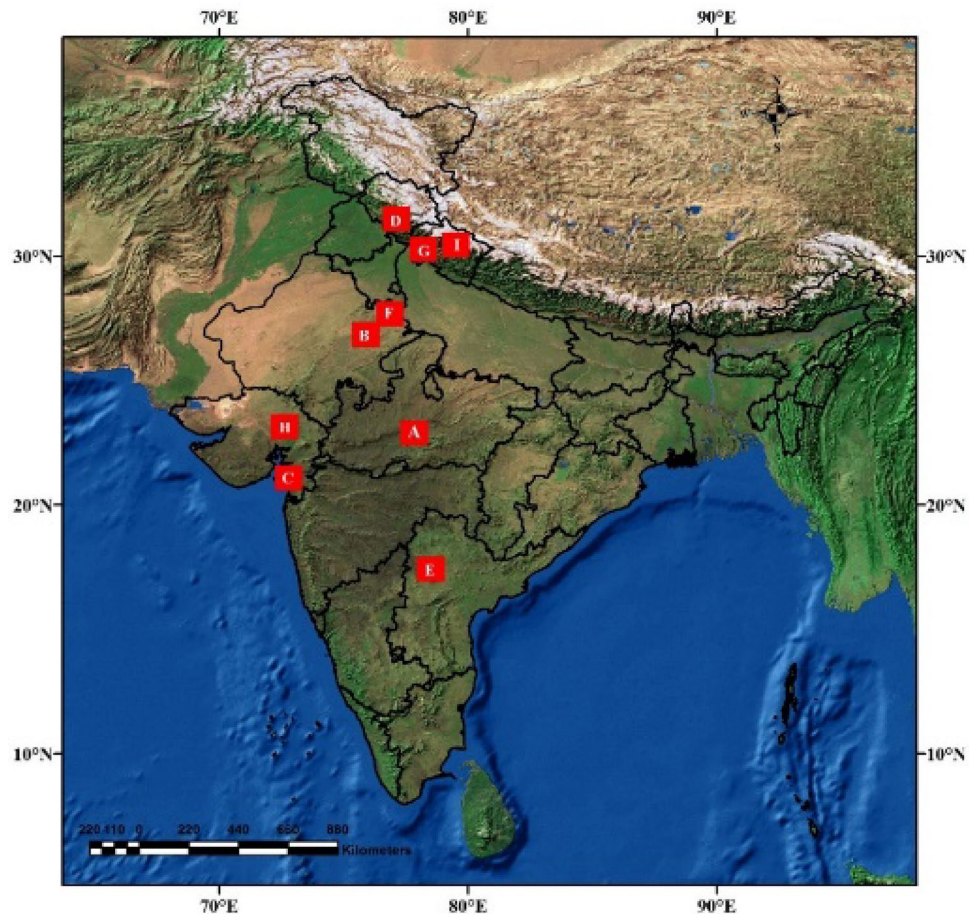
Quality DEM data generation is a challenging task because the DEM generation process is quite complicated. Scientific organizations have been therefore putting constant efforts to produce better DEMs with higher spatial resolution and better accuracy. The Indian Space Research Organization (ISRO) launched the CARTOSAT-1 satellite on 5 May 2005, powered by stereo imaging along the track for cartographic applications and improved the spatial resolution of 2.5 m and radiometric resolution (Muralikrishnan et al. 2006; Giribabu et al. 2013a, b) over its predecessors, with the main objective of topographic mapping. Stereo imaging started with the launch of SPOT-1 in 1986, but the major problem was that it collected data across track stereo mode which brought about radiometric differences between stereo pairs (Ahmed et al. 2007) resulting in poor information. However, in the case of CARTOSAT-1, radiometric parameters of the images are identical because the effects of the Earth's rotation are

taken into consideration so that both Fore and Aft cameras look at the same ground strip when operated in stereo mode (Baral et al. 2016). To understand the application capability of CARTOSAT-1, the accuracy assessment of its products is very important; therefore, the scientific community has assessed its accuracy over the years in several ways. This particular study presents an assessment of the accuracy achievable with CARTOSAT-1-derived 10-m imagery, i.e. geo-referenced, ortho-kit and ortho product over eight major locations in India with varying topographic altitude and landscapes using various robust statistical methods for the very first time.

Study area

The study sites were located all over the Indian sub-continent because of the wide variety of its topography, coupled with unique bio-physical characteristics. The selected study sites were parts of (1) Ahmedabad, (2) Alwar, (3) Bhopal, (4) Chamoli, (5) Dehradun, (6) Hyderabad, (7) Jaipur, and (8) Shimla. Each of this study site selected in (Fig. 1) provides a unique opportunity to evaluate DEM datasets using statistical theories, across

Fig. 1 Study area



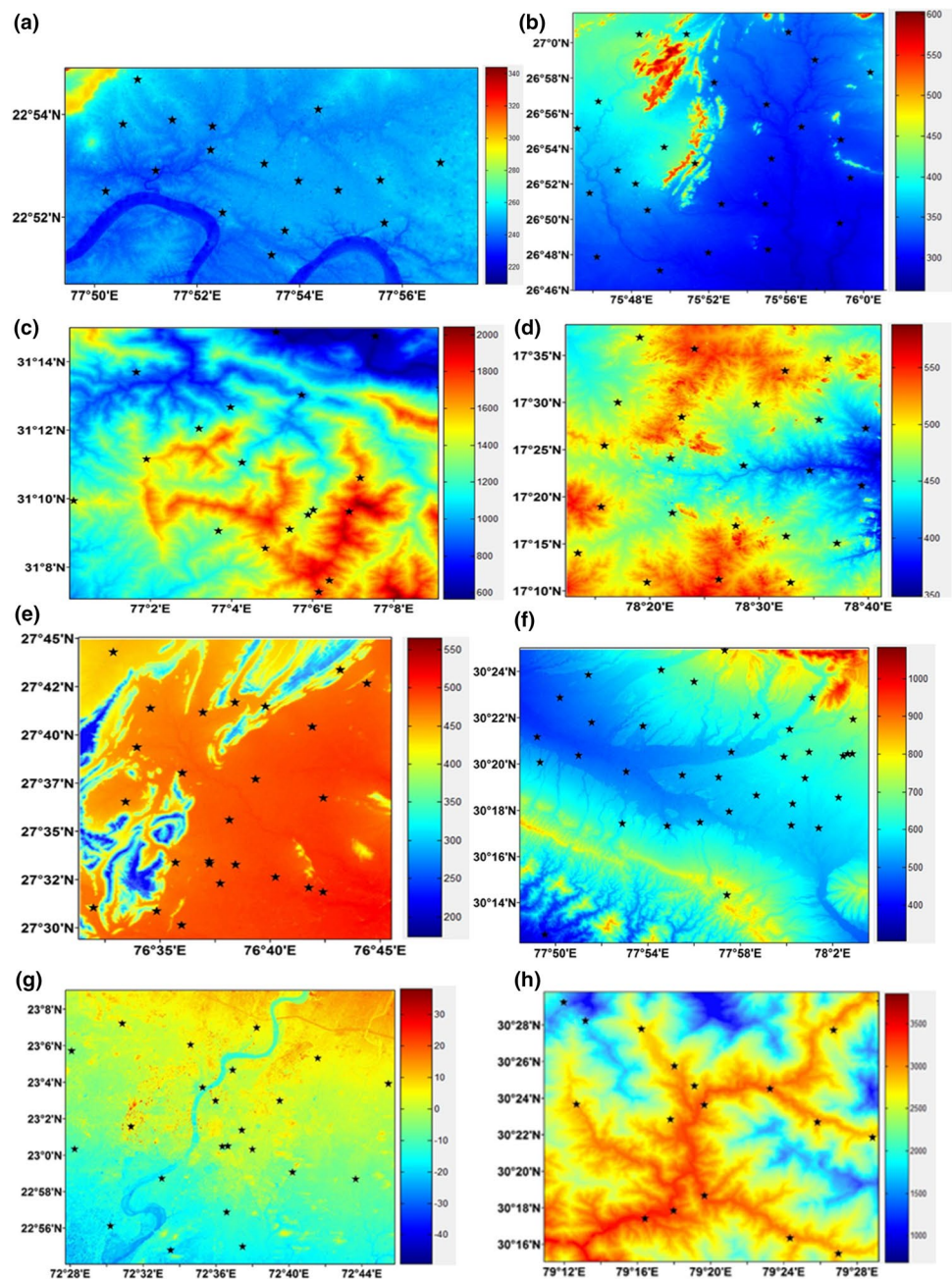
a range of vegetation densities, structural classes as well as a variety of environmental conditions. Figure 2 explicitly shows the variation in elevation over each selected sites. The only exception is that although northeastern India provides a unique topography, none of the sites were selected from this region due to unavailability of DGPS measurements, because collection of field data is difficult in the vast tropical rainforest of Northeast India.

Materials and methods

CARTOSAT-1 DEM

The objectives of the CARTOSAT-1 mission were to provide accurate and nationally consistent elevation information in the spatial domain by utilizing the stereo dataset. “CARTO-DEM”, a national DEM project was undertaken by ISRO for automatic generation and archival of DEM over the Indian region. CARTODEM is generated through autonomous processing of CARTOSAT-1 data, based on the use of limited

Fig. 2 Shows colour maps of CARTOSAT-1 DEM over eight sites, namely **a** Bhopal, **b** Jaipur, **c** Shimla, **d** Hyderabad, **e** Alwar, **f** Dehradun, **g** Ahmedabad, **h** Chamoli



ground control points in long stereo strip pairs. The database was organized as a catalogue of DEM and orthoimage for the entire national frame with DEM posting of 1/3rd arc second (about 10 m at the equator). It provides ellipsoidal height with a standard elevation accuracy of 8 m and planimetric accuracy of 15 m, available in Geo-Tiff format. Approximately, 500 CARTOSAT-1 segments with total number of around 20,000 tile pairs were generated and archived by the National Remote Sensing Centre (NRSC) on Bhuvan portal (http://bhuvan.nrsc.gov.in/bhuvan_links.php) free download with the tiles of $1^\circ \times 1^\circ$ in 30 m resolution. The 10 m CartoDEM is disseminated of the above. In this study, statistical methods have been applied over CARTOSAT-1 DEM of 10 m resolution for the first time with respect to the Differential Global Positioning System (DGPS) datasets observed during the field survey for its accuracy assessment over the Indian region.

DGPS measurements

Precisely, reference stations were established with DGPS measurements. For precise estimation, the GPS observable is processed with the highly precise International GNSS Service (IGS) stations along with precise ephemeris available from garner.ucsd.edu. The data from ten IGS stations [CHUM, COCO, KIT3, Hyde (Hyderabad), LHAZ, PBR2 (Port Blair), POL2, TASH, TEHN, URUM] were used for the establishment of the reference station. The DGPS observation was collected for a minimum period of 72 h with an epoch of 15 s and processed with IGS stations. GAMIT software developed by MIT was used for GPS data processing having capability of retrieving coordinates with millimetre precision (Herring et al. 2010). It computes ionosphere and tropospheric delay, because multipath and ambiguity in satellite orbit determination are the major sources of errors. These errors are modelled and filtered out to improve the accuracy of the coordinates. GAMIT incorporates a weighted least square algorithm to estimate the relative position of the station, orbital and Earth orientation parameters, zenith delays, and phase ambiguities by fitting to doubly differenced phase observations. The baseline estimation using a longer baseline estimation algorithm helps to compute the distance between the station and IGS stations. The reference points were used for the establishment of the static station with an epoch of 15 s and observable periods of 1 h. The static points are the GCP points processed with the Gamit S/w, and these GCPs are used for the accuracy assessment of the DEM.

Factors controlling horizontal accuracy of a DEM

There are many factors which control the accuracy of the DEM. It is largely affected by the density and spacing of the

DEM points, break lines of the horizontal scale of the final orthophoto, and the characteristic features of the land (Rawat et al. 2013). Apart from these, the accuracy of DEM-derived products mainly depends on the source of the elevation data which includes the technique for measuring elevation either on the ground or by remote sensing, location of samples and density of samples, and the DEM creation methodology from the elevation data. The data model, or structure of the elevation data, i.e. grid, contour and triangular irregular network, depends on the horizontal resolution and vertical precision at which the elevation data are represented, and the algorithms used to calculate different terrain attributes (Theobald 1989; Chang and Tsai 1991; Florinsky 1998).

Calculating horizontal accuracy of selected GCP and CARTOSAT-1 DEM

To determine the horizontal accuracy of selected points over the eight sites, robust statistical analysis was done by computing the following elevation error, minimum error, maximum error, mean error, standard deviation error and root mean square error (RMSE) using the formulas below:

Elevation error

The elevation error was determined by calculation of the vertical differences between CARTO DEM and the GCP points.

$$\text{Elevation error (ER)} = Z_{\text{DEM}} - Z_{\text{GCP}}$$

Maximum and minimum error

Maximum error represented the positive maximum elevation differences between the extracted DEM and GCP, while the minimum error represented the maximum negative elevation differences.

Mean error

Mean error shows the central tendency of the distribution, for the elevation values over an area.

$$\text{Mean error (ME)} = \frac{\sum_{i=1}^n Z_{\text{dif}(i)}}{n}$$

Standard deviation error

Standard deviation error represents the departure of each value from the mean.

$$\text{Standard deviation error (STD}_{\text{err}}) = \sqrt{\frac{\sum_{i=1}^n (Z_{\text{dif}(i)} - \text{ME})^2}{n - 1}}$$

Root mean square error (RMSE)

To compare the overall performance of the CARTO DEM, RMSE indices were calculated for validation of accuracy. Areas with low RMSE values have better accuracy than the areas with higher RMSE values.

$$\text{Root mean square error (RMSE)} = \sqrt{\frac{\sum_i (Z_{\text{dif}(i)})^2}{n}}$$

where Z_{DEM} is the elevation of a point extracted from the CARTOSAT DEM, Z_{GCP} is the elevation of the ground control point taken by DGPS, and n is the total number of observations.

To visualize the error distributions in each DEM, quantile–quantile plots (Q–Q plots) were created for examination based on the Shapiro–Wilk’s normality test ($p > 0.05$). This test is usually done for normality analysis. The test rejects the hypothesis of normality when the p value is less than or equal to 0.05 (Shapiro and Wilk 1965). This normality test passes only when no significant departure from normality is found. Further inspection of the skewness and kurtosis measurements is also carried out to compute the appropriate statistical measures of central tendency, dispersion, symmetry and peakedness of the dataset (Fig. 3).

Results and discussion

The stereo blocks of CARTOSAT-1 DEM generated at 10 m spatial resolution was subjected to robust statistical methods for accuracy assessment. The horizontal accuracy of DEM provided us evidence of the accuracy level of the selected GCPs with respect to CARTOSAT-1 10 m spatial resolution gridded data product and horizontal plane of the Earth’s surface. Accuracy assessment over each site was carried out separately to understand the error levels in each case due to its unique topography. The adaptation of eight sites also facilitates the examination of regional applicability of the DEM data over the Indian subcontinent. The regions were defined under three broad categories according to its average elevation low, moderate and high. This grouping was done to understand which topographical type can have maximum errors and which type of topography has almost negligible error or are rather error free.

Bhopal, Jaipur and Ahmedabad fall under the lowland category, since the average height of these places are 247 m, 346 m and 3 m, respectively, Alwar and Dehradun fall under

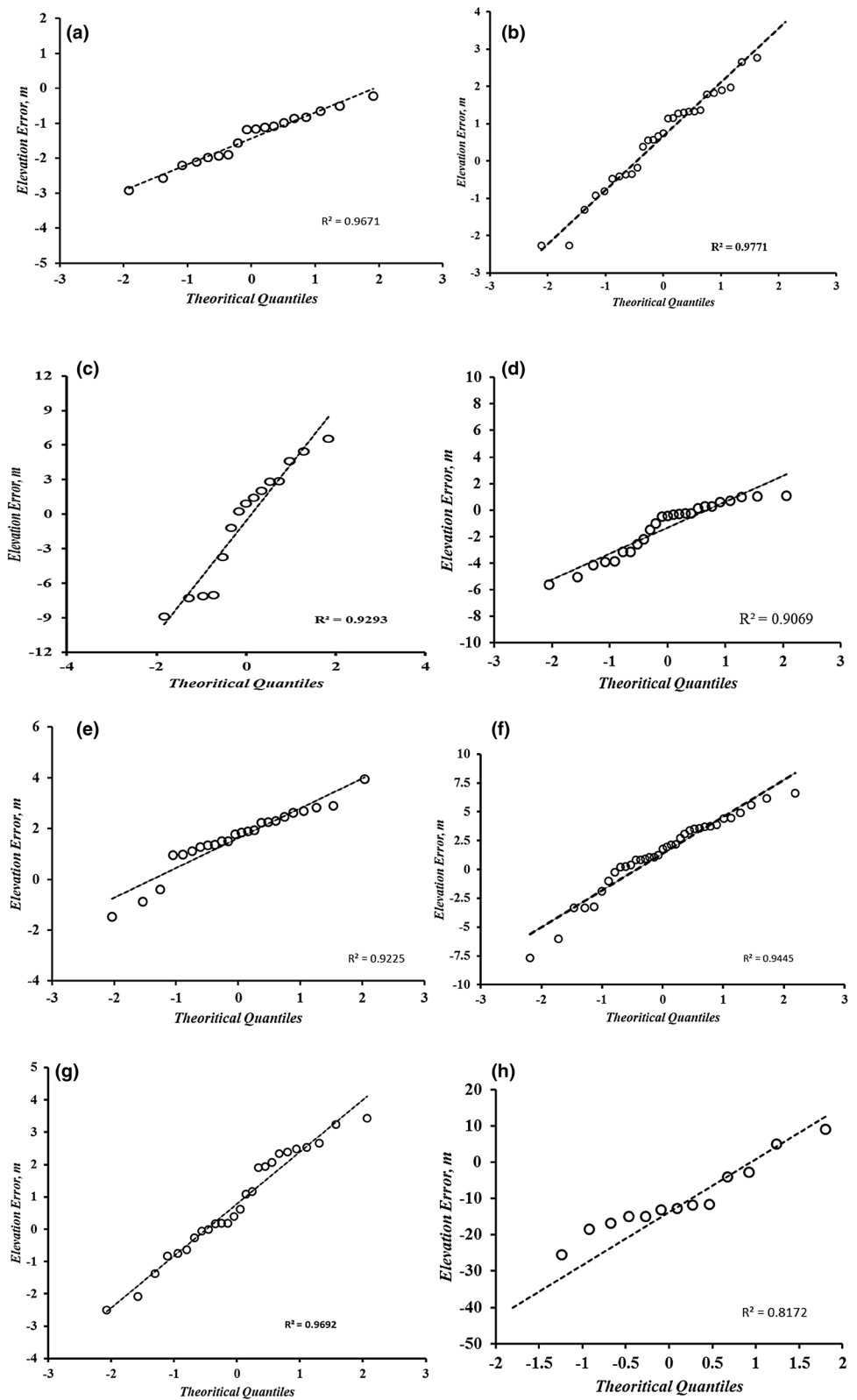
moderate topographic land surface with a height of 500 m and 570 m, whereas Shimla and Chamoli fall under highland with an average height of 1353 m and 1446 m.

For comparison and accuracy assessment, the American Society of Photogrammetry and Remote Sensing (ASPRS) recommends a minimum of 20 checkpoints in each of the major land cover categories (ASPRS Lidar Committee 2004). Keeping this factor in mind we have taken a minimum of 20 points for each site. Table 1 gives a vivid view of the parameters we have considered for our study.

The maximum error was observed to be in Chamoli 62.1 which clearly indicates that high land exhibits greater error than the other categories of terrain type. It is known that RMSE not only increases with variance of the errors, but also increases with the variance of the frequency distribution of error magnitudes. Thus, the rise in error frequently increases the RMSE. Chamoli witnesses an RMSE error of 28.82, which shows that the DEM gives unstable results over the highland region and the accuracy level decreases due to overall rise in error factor. A similar case was observed in Shimla where RMSE goes up to 6.75. Usually high-altitude himalayan terrain exhibits extreme geometric distortion along north-facing (dilation) and south-facing (compression) slopes as observed in satellite stereo data with high look angles (Giribabu et al. 2013a, b) may be the main reason for high errors to crop up. It is observed that although Dehradun is categorized under moderate elevation terrain type, since it is a valley region the RMSE is as high as 6.24 in the Dehradun valley because of the forest cover and the surrounding wall of lower Himalayas which introduces elevation error over this type of terrain. In case of Alwar, the case is quite different. The land belongs to moderate terrain type and its RMSE and mean error are considerably low. However, Bhopal, Jaipur and Ahmedabad exhibit very low RMSE, showing a high accuracy rate of CARTOSAT-1 DEM datasets at 10 m spatial resolution.

Further, Shapiro–Wilk’s normality test ($p > 0.05$) was carried out, and inspection of the skewness and kurtosis measures was also done to understand the symmetrical pattern of the dataset. Q–Q plots were obtained to analyse and visualize the error quantitatively more clearly over the eight selected study areas. The diagram below shows the Q–Q plots where elevation error is plotted against the theoretical quantiles. It has been observed that in all the eight cases, the Shapiro–Wilk’s normality test showed that the error distribution was approximately normal in all the cases, since the p value was greater than 0.05 in all cases. The p values were 0.59, 0.92, 0.15, 0.11, 0.31, 0.32, 0.40, and 0.32 in the respective sites. This clearly proves that there is no abnormality observed within the selected areas. Further, Bhopal, Hyderabad and Ahmedabad show a negative kurtosis value, proving that the tail in these cases is not heavy, so the distribution of the error is very

Fig. 3 Shows Q–Q plot of eight selected study areas. **a** Bhopal, **b** Jaipur, **c** Shimla, **d** Hyderabad, **e** Alwar, **f** Dehradun, **g** Ahmedabad, **h** Chamoli



less over lowland, whereas in the moderately elevated land the kurtosis value is slightly positive proving that

the error distribution is moderate in this region. Chamoli and Shimla have a kurtosis value greater the four, showing

Table 1 Summary evaluation parameters of DEM errors

Study area	Terrain type	No of GCP	Min error	Max error	Mean error	STD error	RMSE
Bhopal	Low	20	−2.93	−0.22	−1.36	1.59	1.61
Jaipur	Low	29	−2.27	4.05	0.67	1.62	1.58
Shimla	High	20	−11.46	17.56	−0.16	6.93	6.75
Hyderabad	Low	25	−5.63	1.07	−1.33	2.46	2.40
Alwar	Moderate	25	−11.38	3.96	1.11	3.07	3.02
Dehradun	Moderate	38	−7.66	26.35	2.65	6.41	6.24
Ahmedabad	Low	27	−2.50	12.09	1.20	2.98	2.91
Chamoli	High	20	−59.10	62.21	−14.06	29.53	28.82

that the tail is heavy and has large error distribution over the highlands.

Conclusion

This study examined the quality of CARTOSAT digital elevation models with respect to eight study sites spread over the Indian subcontinent [(1) Bhopal, (2) Jaipur, (5) Shimla, (6) Hyderabad, (7) Alwar, (8) Dehradun, (9) Ahmedabad, (10) Chamoli]. First, the basic characteristics of the DEM were described. Then, comparisons of the DEMs vertical accuracy were done using GPS reference data. Finally, the error was analysed using robust statistical measurements. The results of RMSE for terrain elevation range from 1.61 m to 28.82 m in varied topography. The Q–Q plots for CARTO DEM indicated that the data conformed with approximately normal distribution, representing a sigmoid-type function with a significant deviation from the fit line at some places. The following study indicates that the CartoDEM is very accurate in lowland and moderately elevated land. Exceptions are observed only in highlands where accuracy is comparatively poor for CARTOSAT-1 DEM, but in the near future some more correction methods can be explored to rectify the error in the highland region. Overall, CARTOSAT-1 DEM was prepared with the Indian perspective, so we can conclude that the accuracy of the DEM is quite high, because most of the Indian terrain comes under plains and moderate undulation except the northern highlands. Thus, it can be concluded that CARTOSAT-1 DEM can be used for geospatial applications for the entire Indian region with a good accuracy.

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