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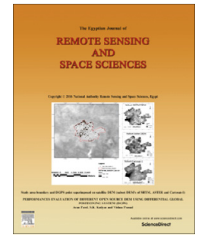

RESEARCH PAPER

Performances evaluation of different open source DEM using Differential Global Positioning System (DGPS)

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Abstract In Open sources DEMs such as SRTM, ASTER and Cartosat-1, various factors affecting the accuracy of satellite based DEM such as errors during data collection, systematic errors and unknown errors that are geographically dependent on terrain conditions cannot be avoided. For these reasons it is very necessary to check and compare the performances and validation of the above mentioned different satellite based DEMs. Accuracy assessment of these DEM has been done using DGPS points. For these points proper interpolation of the surface was developed using different interpolation techniques. For the generation of the surface the first step was converting the satellite based DEMs height into linear interpolation contour maps of 1 m interval. Then came selecting random sample points on the contour line and generating the interpolated surface using different interpolation techniques such as IDW, GPI, RBF, OK and UK, LPI, TR and BI, which are commonly used in geomorphology research. This interpolated surface helps in proper representation of the terrain and was checked under different terrain surfaces. For validation of DGPS points the height was taken for ground control points and standard statistical tests such as ME and RMSE were applied. From above investigation, it is reveals that above mention DEMs which are used for study. Cartosat-1 (30 m) data product is better than SRTM (90 m) and ASTER (30 m) because it had produced low RMSE of 3.49 m without applying the interpolation method. Investigation also reveals after applying the interpolation techniques on this data error can be reduced. In the case of Cartosat-1 and SRTM, low RMSE and ME were produced by the BI method, where Cartosat-1 DEM had an RMSE of 3.36 m with ME of −2.74 m, respectively. But in this case, RMSE and ME of SRTM is 2.73 m and −0.36 m, respectively. BI is designed for image processing and can be used for imagery were a maximum height variation in satellite DEM and terrain height is minimum. But in the case of ASTER DEM, the GPI method with a high polynomial order of 9 had

Abbreviations: SRTM, Shuttle radar topographic mission; ASTER, Advanced Space Borne Thermal Emission and Reflection Radiometer; DGPS, Differential Global Positioning System; IDW, Inverse Distance weight; GPI, Global Polynomial Interpolation; RBF, Radial Basis Function; OK and UK, Ordinary and Universal Kriging; LPI, Local Polynomial Interpolation; TR, Topo to raster; BI, Bilinear interpolation; ME, Mean Error; RMSE, root mean square error; DEM, digital elevation model

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produced a low RMSE of 4.99 m. The GPI method can be applied where maximum height variation in satellite DEM and in terrain is more.

1. Introduction

DEM is one of the most popular data models used for the purpose of terrain modeling. It is a grid based matrix structure, which records topological relations between data points implicitly. Since this data structure reflects the storage structure of digital computers (i.e. A grid can be stored as a two dimensional array of elevations), the handling of elevation matrices is simple, and many terrain analysis algorithms based on this structure tend to be relatively straight forward. DEM is an array representation of squared cells (pixels) with an elevation value associated to each pixel (Manuel, 2004). DEMs had a wide range of applications in topography, geomorphology, vegetation cover studies, tsunami assessment, and urban studies. There are various ways of obtaining DEMs either by contour lines, topographic maps, field surveying using auto level, total station and GPS, Photogrammetry techniques, radar interferometry, and laser altimetry (Manuel, 2004). Satellite based DEM such as SRTM, ASTER and Cartosat-1 are freely available and widely available.

The SRTM provides the most complete, highest resolution available DEM of the Earth. It is based on the principle of interferometric SAR or InSAR, which uses phase-difference measurements derived from two radar images acquired with a very small base to height ratio (typically 0.0002) to measure topography (SRTM project). In quantitative terms, the cartographic products derived from the SRTM data are sampled over a grid of 1 arc-second $\times$ 1 arc-second (approximately 30 m $\times$ 30 m). The SRTM global data for the rest of the World other than the USA is available at 3 arcs second (90 m). The product consists of seamless raster data, which is provided according to a user specified area of coverage. The SRTM 'finished' data meet the absolute horizontal and vertical accuracies of 20 m (circular error at 90% confidence) and 16 m (linear error at 90% confidence) respectively, as specified for the mission. The vertical accuracy is significantly better than the 16 m. It is closer to ± 10 m (Rabus et al., 2002; Sun et al., 2003). Its application is the concern of various studies which were conducted on topography (Falorni et al., 2005; Koch and Lohmann, 2000), geomorphology (Guth, 2003; Stock et al., 2002), vegetation cover studies (Kellndorfer et al., 2004), tsunami assessment (Blumberg et al., 2005), and urban studies (Gamba et al., 2002). SRTM data verification was performed using various altimetry data (Helm et al., 2002; Sun et al., 2003) and digital elevation models (Muller, 2005; Jarvis et al., 2004;Smith and Sandwell, 2003).

The ASTER DEM product is generated using bands 3N (nadir-viewing) and 3B (backward-viewing) of an ASTER Level-I A image acquired by the visible near infrared (VNIR) sensor. The VNIR subsystem includes two independent telescope assemblies that facilitate the generation of stereoscopic data. The band-3 stereo pair is acquired in the spectral range of 0.78 and 0.86 µm with a base-to-height ratio of 0.6 and an intersection angle of about 27.7°. There is a time lag of approximately one minute between the acquisition of the nadir and backward images. Each frame covers an area of 60 km $\times$ 60 km with an output DEM resolution at 30 m. ASTER DEM has enhanced accuracy due to the use of multiple ASTER images over the same area. ASTER DEM is available in Geo-tiff format with signed 16 bits and is in geographic projection with latitude–longitude. Posting interval is 1 arc second and the ASTER DEM coverage is available for north 83° to south 83° with 22,600 tiles. DEM accuracy is around 7–14 m.

Indian Space Research Organization (ISRO) has launched CARTOSAT satellite, which is a mission of acquiring DEM of the country. The national level DEM generation using the CARTOSAT data at 10 m resolution is under preparation at ISRO. The primary mission goal of CARTOSAT-1 is to generate a current, accurate and nationally consistent DEM throughout the country to facilitate the user communities of remote sensing and cartography. It is anticipated that the DEM will be useful in providing an elevation reference of the existing topographic conditions. In the GIS environment, DEM will provide a terrain model to facilitate drainage network analysis, watershed demarcation, erosion mapping, contour generation and quantitative analysis like volume-area calculation. DEM will enable generation of ortho-rectified images which can be used as raster maps to define and demarcate features such as land use, topography, roads, rivers, water-bodies, and watershed. They may also be used to establish accurate geographic locations of features and make measurements. Other applications of DEM and Ortho-image include scene simulation and fly through visualization for appreciation of terrain relief. Accuracy of the DEM is around 8 m in Z scale (www.isro.gov.in).

Interpolation techniques are based on the principles of spatial autocorrelation, which assumes that closest points are more similar compared to further ones. The literature reveals a great deal of interpolation methods which are generally classified as global and local approaches. Global interpolations use all the available data to provide estimates for the points with unknown values. In local interpolation methods such as IDW, local polynomial, and RBF use only information in the vicinity of the point being estimated. Global interpolators are often used to remove the effects of major tends before using local interpolators to analyze the residuals (Burrough and McDonnell, 1998; Johnston et al., 2001). Different interpolation methods applied over the same data sources may result in different results and hence it is required to evaluate the comparative suitability of these techniques. Selection of interpolation techniques are based on the initial sampling data points and the number of samples taken, which greatly effect the quality of DEM. Many interpolation techniques exist and every technique has its advantages and disadvantages. Many authors have done comparative studies on the interpolation accuracy. Some studies revealed that the Local deterministic method and interpolated heights are assured to be within the range of the samples used. It does not produce peaks, pits, ridges or valleys that are not already present in the input samples and adapts locally to the structure of the input data. It does not require input from the user and works equally well for regularly as well as irregularly distributed data (Watson, 1992). But some authors had indicated that among the many existing interpolation techniques, geostatistical ones perform better than others (Creutin and Obled, 1982; Laslett and McBratney, 2002; Zimmerman et al., 1999; Wilson and Gallant, 2000). Zimmerman et al. (1999) and Arun et al., 2013 revealed that kriging yielded better estimations of altitude than IDW irrespective of the sampling pattern and landform type. In this paper the author demonstrated the ability of kriging to adjust itself to the spatial structure of the data. However, in other studies done by the following authors Weber and Englund, 1992; Gallichand and Marcotte, 1993; Brus et al., 1996; Declercq, 1996; Aguilar et al., 2005 it was revealed that neighborhood approaches such as RBFs or IDW were found to be as accurate as kriging or even better. Application of the ANUDEM interpolation method is designed for the creation of hydrological correctness of the terrain surfaces. But the ambiguity remains the central question which is the most appropriate method for different terrain conditions (Weber and Englund, 1992, 1994;Carrara et al., 1997; Robeson, 1997; Arun et al., 2013).

There are various factors affecting the accuracy assessment of satellite based DEM such as error during data collection (Rodgriguez et al., 2006). Further errors can be broadly classified into two categories such as systematic and random error. Systematic error which occur due to deficiency in orientation of stereo image with photogrammetrically determined elevation values (Mukherjee et al., 2011) another type of error comprises unknown combinations of errors (random error) which cannot be avoided such as geographically depending terrain conditions (Holmes et al., 2000). The other issues related to DEM accuracy are grid spacing and interpolation techniques were identified by few authors (Mukherjee et al., 2011). Mukherjee et al., 2013 has done experiment on accuracy assessment of SRTM and ASTER DEM. He had revealed that RMSE for the ASTER, SRTM and Cartosat-1 DEM calculated is 6.08 m, 9.2 m and 4.83 m with ME of −2.58 m, −2.94 m and 0.19 m, respectively. But error in satellite remains the central question before it's use in terrain mapping, so there is a need to evaluate the performances of this DEM. In this paper, we have compared and evaluated the performances of the SRTM, ASTER and Cartsat-1 DEM, by generating contour maps of 1 m interval from the satellite based DEM. Selecting random sample points on the contour line and then generating the interpolated surface using different interpolation techniques such IDW, GPI, RBF, Kriging, LPI, TR and BI, commonly used in geomorphology research (Weber and Englund, 1994; Zimmerman et al., 1999; Mitas et al., 1999; Aguilar et al., 2005; Chaplot, 2006; Arun, 2013). This will help in finding out the best performances of DEM under sensitivity condition of the terrain using various interpolation techniques used by geomorphologies. Performance evaluation of DEM can be done by using DGPS point taken on the ground. Both datasets are based on the same vertical datum World Geodetic System 1984 (WGS84) world wield accepted datum model. Standard statistical tests such as Mean Error (ME) and Root mean square error (RMSE) were performed on it.

2. Study area and data resources

The present paper is a case study of Maulana Azad National Institute of Technology Bhopal (MANITB), in the capital city of state of Madhya Pradesh, India. The topology of the Bhopal city is highly uneven and it has small hills within its boundaries. The geographic extent of the study area is 23°11'30.44" to 23°27'39.96" N latitude and 77°26'32.86" to 77°27'59" E longitude with an average elevation of 523 m. Consider DEM such as SRTM, ASTER and Cartosat-1 and there subset DEMs are shown in Fig. 1. Horizontal and vertical datum's of all DEM are shown Table 1. where the world geodetic system 1984 (WGS84) is represented by the shape of the ellipsoid and was calculated based on the hypothetical equipotential gravitational surface of the earth. But the vertical datum is referred to mean sea level (MSL) as an orthometric height which is determined by the earth gravity model (EGM96) as a geoid model. A significant difference exists between this mathematical ellipsoid model and the geoid model. The most mathematically sophisticated geoid can only approximate the real shape of the earth as shown in Fig. 2. If this ellipsoid vertical datum is used, height above the ellipsoid will not be the same as MSL and direct elevation readings for most locations will be embarrassingly off. The surface of global undulations was calculated based on altimetric observations and very precise (up to two centimeters) measurements taken from the TOPEX/POSEIDON satellite. These data are represented in the EGM96, which is also referred to as the spherical harmonic model of the earth's gravitational potential (Witold, 2003). But in the case of DGPS default vertical datum is WGS 84 and the height computed relative to this (Kaplan and Hegarty, 2006). But the elevation of a point on the earth's surface computed from MSL can vary from GPS derived elevation because of the WGS84 ellipsoid and EGM96. The Geoid surface is an equipotential or constant geopotential surface which corresponds to MSL (local Datum). The geoid height/geoid undulation (N) the difference in height between geoid (h) and ellipsoid (H) at a point is shown in Fig. 3, and represented in Eq. (1)

$$h = H + N \tag{1}$$

As per specifications of Magellan Promark-3 single frequency DGPS system uses the Stop-n-go method with a horizontal accuracy of 0.012 m + 2.5 ppm and a vertical accuracy of 0.015 m + 2.5 ppm and data are processed in GNSS solution after post-processing.

3. Methodology

Commonly used interpolation approaches have been evaluated from satellite based DEM with reference to the study area and the adopted methodology is summarized in Fig. 4.

- In this SRTM DEM, ASTER DEM and Cartosat-1 DEM were downloaded from the above mentioned website in Table 2, subsetting area of interest (AOI) from DEMs as shown in Fig. 1.
- Following two steps involved in drawing the automated contour on the raster DEM in ArcGIS Spatial analyst tool.

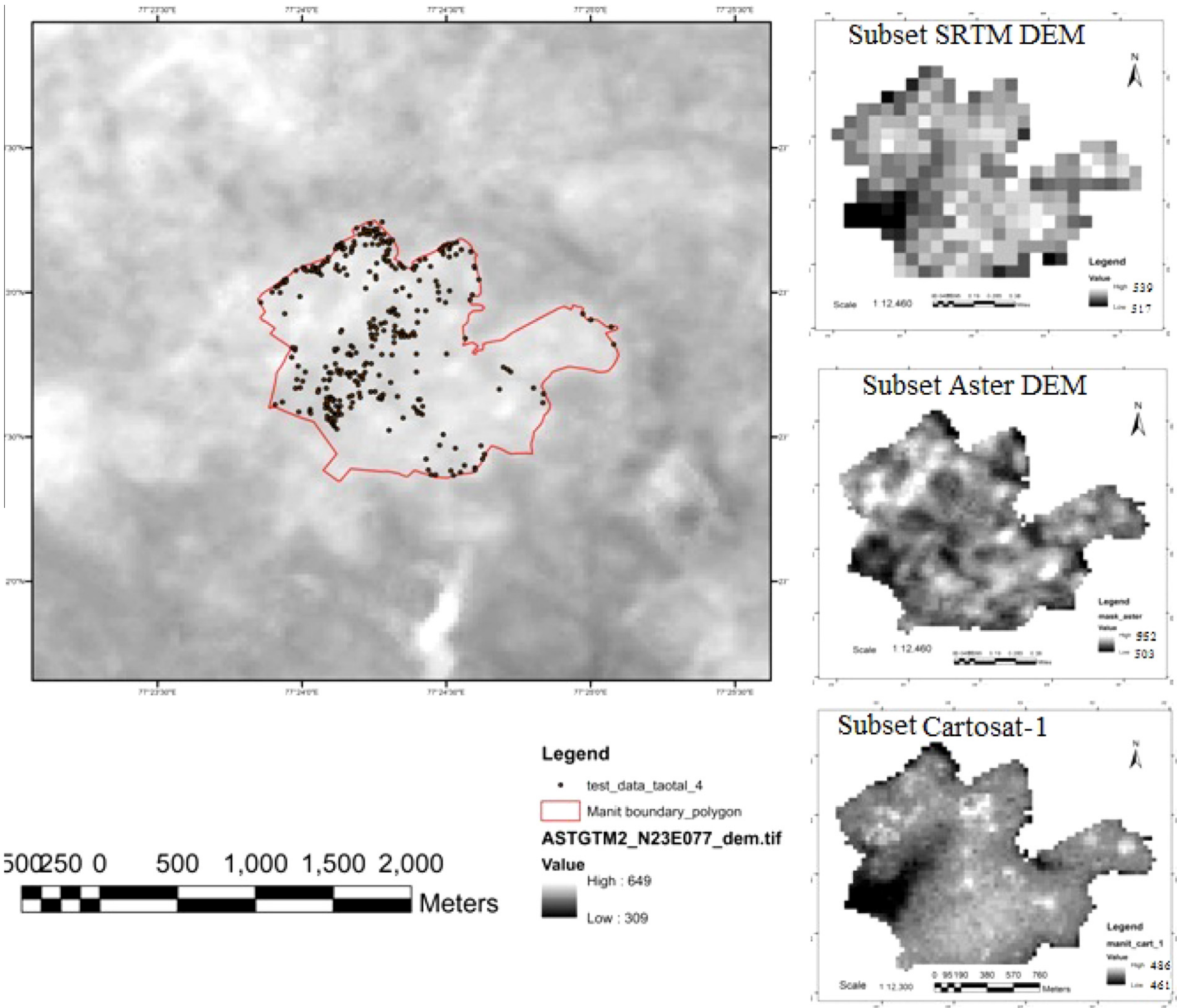

Figure 1 Study area boundary and DGPS point superimposed on satellite DEM (subset DEM's of SRTM, ASTER and Cartosat-1).

Table 1 Represents horizontal and vertical data.

Data	Horizontal data	Vertical data
SRTM DEM	WGS84	EGM96
ASTER DEM	WGS84	EGM96
Cartosat DEM	WGS84	WGS84

Source: ASTER and SRTM data user Handbook.

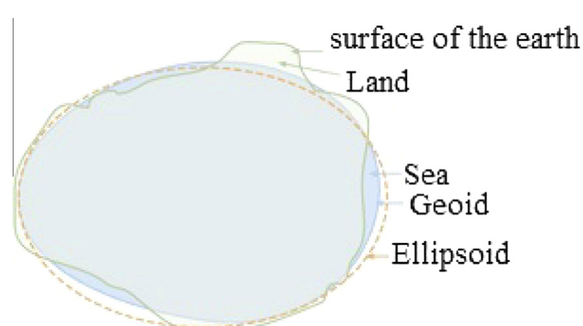

Figure 2 Model of the Earth.

- ➢ Detecting a contour line that intersects a raster cell or triangle.
- ➢ Drawing the contour line through the raster cell or triangle (Jones et al., 1986) using linear interpolation which assumes that a constant gradient between end nodes of the edge can determine the contour line's position along the edge. After all the positions are calculated they are connected to form the contour lines (Chang, 2008).
- ➢ Drawing a contour interval of 1 m from this satellite based DEM as shown in Fig. 5.

- After drawing the contour line, then selection of a random point (2147 points) on the vertices of this line tool used takes place as shown in Fig. 5. Fig. 6 shows the DEM with contour lines with 1 m interval and selected vertices to point on the contour line.

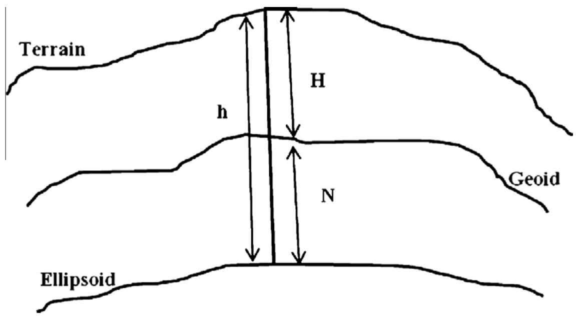

Figure 3 Relation between ellipsoid height, orthometric height and geoid undulation.

- Generation of vertice point will help in regenerating the actual surface using a different interpolation method. Then raster surface has been generated from reference DEM using different interpolation methods, namely IDW, Kriging, GPI, LPI, RBF and Topo to raster.
- Accuracy assessment of generating surfaces has been evaluated using well distributed DGPS points (830 points) and is super imposed on the satellite DEMs as shown in Fig. 1.
- Mathematical analysis has been done by calculating the deviations of interpolated height values from corresponding predicted and observed values in terms of ME and RMSE obtained from Eq. (2) and (3). The ME tells us whether a set of measurements consistently underestimate (negative ME) or overestimate (positive ME) the true value. The RMSE is a single quantity characterizing the error surface, and mean error reflects the bias of the surface (Mukherjee et al., 2011).

  ➢ The equations are as follows:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(Z^{*} - Z) \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z^{*} - Z)^{2}} \tag{3}$$

where
Z^{*} = observed values of the height
Z = modeled values of the height

4. Result and discussion

4.1. Comparative analysis of interpolation method

The first analysis was made on the performance comparison of satellite based DEM such as SRTM, ASTER and Cartosat-1 DEM without applying any interpolation method. The height values were directly taken from satellite DEM without interpolation. The investigation was carried out on overall terrain. Analysis was carried out using 830 well distributed DGPS points along the study area as shown in Fig. 1. From the above analysis it is revealed that Cartosat-1 30 m resolution produced the Lowest RMSE of 3.49 m with an ME of −2.71 m. But in the case of SRTM and ASTER DEM is comparatively higher than Cartosat-1 as shown in Table 3.

Second comparative analysis were performed through the conversion of the satellite based DEMs height into linear interpolation contour maps of 1 m interval. Then selecting random sample points takes place on the contour line followed by the generation of the interpolated surface using different interpolation techniques such IDW, GPI, RBF, OK , UK, LPI, TR and BI. From the above investigation it is clear that in the case of Cartosat-1 and SRTM DEM, the BI method has reduced the

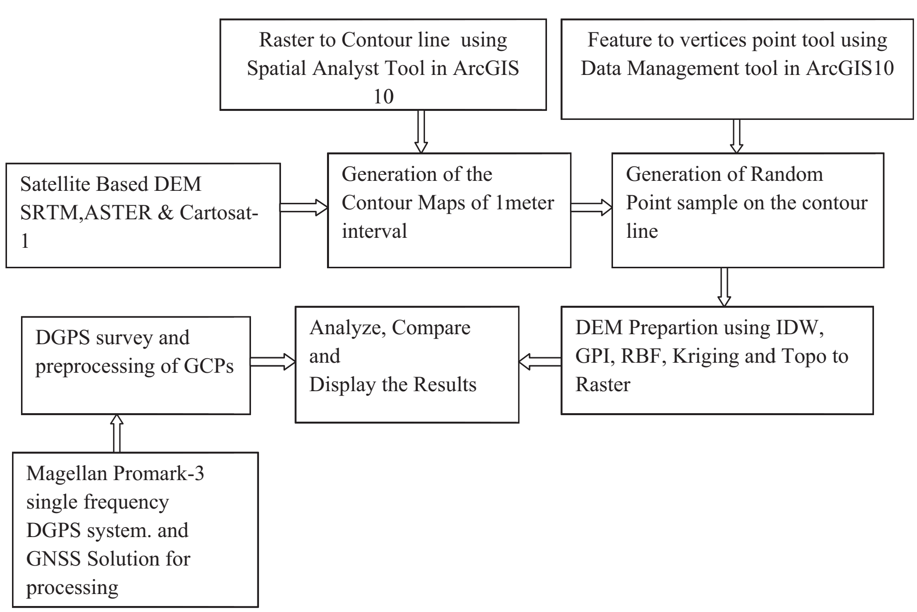

Figure 4 Methodology.

Table 2 Data resource description of the study area Bhopal.

S. No	Image used	Resolution (arc sec)	Satellite	Download	Date of Procurement
1	SRTM DEM	3 (90 m)	Shuttle Radar	ftp://e0srp01u.ecs.nasa.gov and http://seamless.usgs.gov/	Feb 2005
2	ASTER DEM	1 (30 m)	ASTER GDEM	http://earthexplorer.usgs.gov/	17/10/2011
3	Cartosat-1 DEM	1 (30 m)	Cartosat-1	http://bhuvan-noeda.nrsc.gov.in/download/download/download.php?c = s&s = C1&p = cdv2	20/08/2011

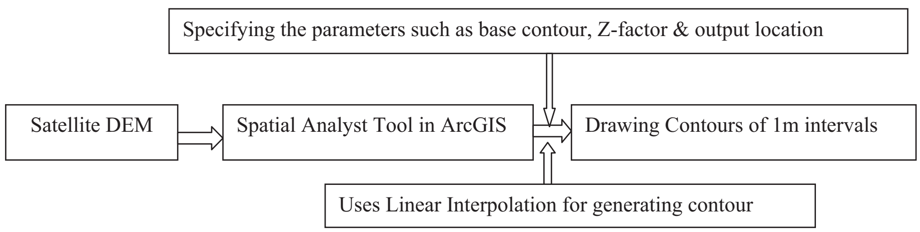

Figure 5 Generate contour on satellite DEM using ArcGIS (Spatial Analyst Tool).

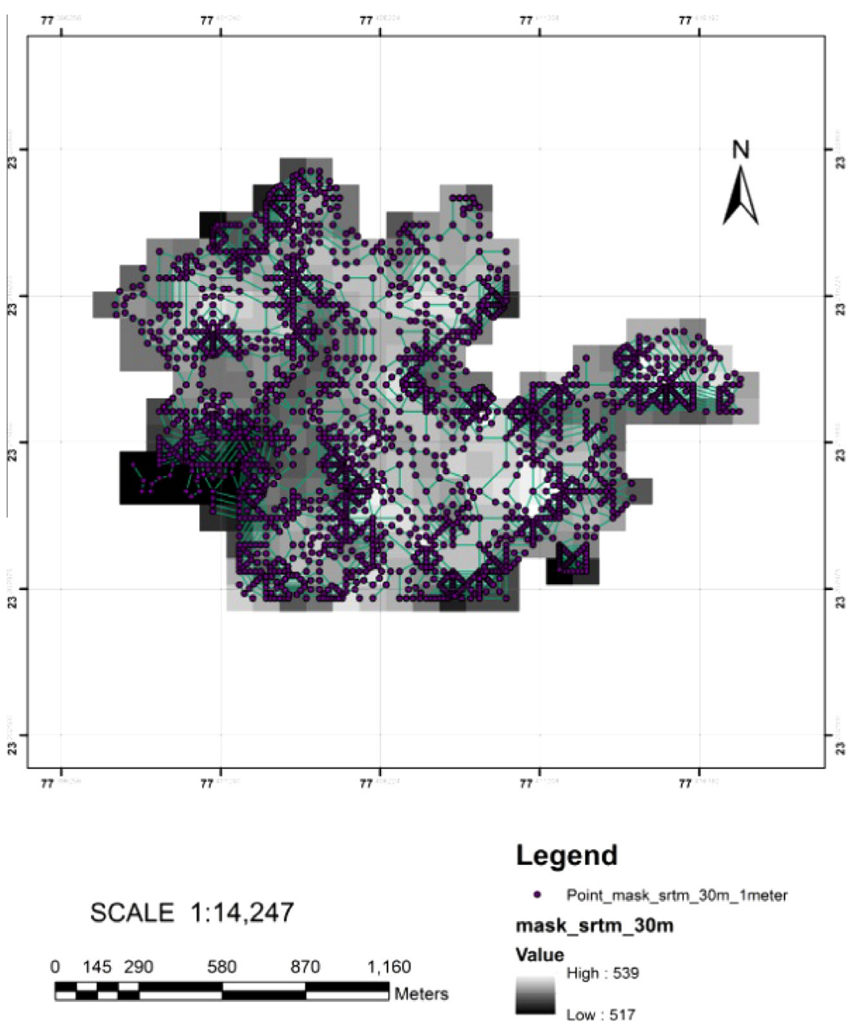

Figure 6 Satellite DEM with contour lines with 1 m interval and selected vertices to point on the contour line.

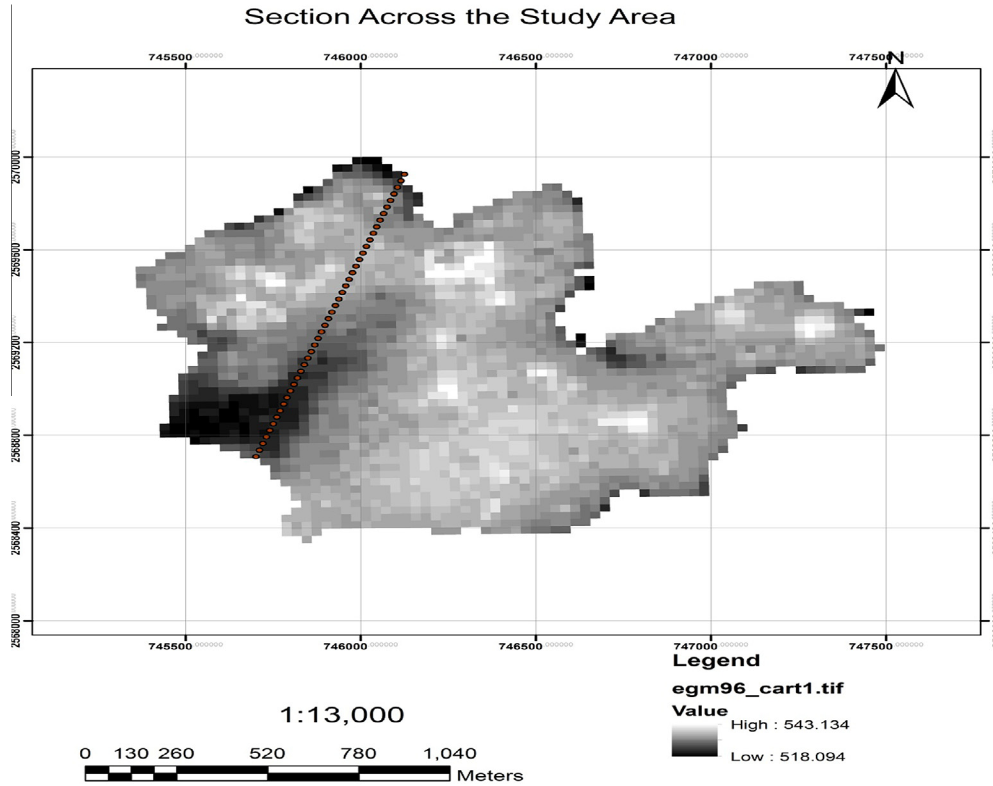

Figure 7 The section line along the satellite DEM's.

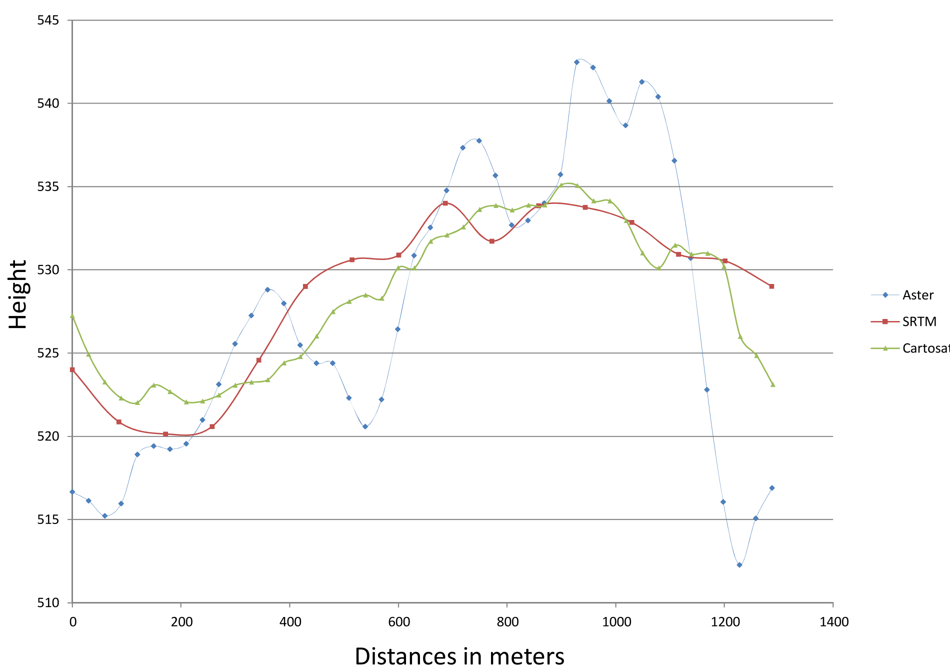

Figure 8 The variation of height in three DEMs along the sectional line.

RMSE and ME. In the case of SRTM data RMSE is 2.73 m with ME −0.36 m and ASTER data RMSE of 3.36 m with an ME of −0.274 m as shown in Table 4. The variation of heights in satellite DEMs is seen by considering a section along it as shown in Fig. 7 and variation of height in satellite DEMs is shown in Fig. 8. There is a high variation of ASTER as compared to SRTM and Cartosat-1 DEMs but SRTM and Cartosat-1 approximately have the same variation of height as shown in Fig. 8. Further comparison of variation of height is done by considering statistical parameters of satellite DEMs

Table 3 Comparativel analysis of different satellite based DEM without interpolation.

	SRTM	ASTER	Cartosat-1
ME	−0.61	0.45	−2.71
RMSE	3.72	6.03	3.49

Table 6 Shows differences in height variation with respect to DGPS.

	$\Delta H_{\max}$	$\Delta H_{\min}$	ΔH_{mean}	$\Delta Std.dev$
SRTM	2	5.64	3.01	−0.04
ASTER	15	14	2.02	2.19
Cartosat-1	6.14	6.74	6.34	−0.5

Where
$\Delta H_m ax$ = maximum height in satellite DEM – maximum height in DGPS.
$\Delta H_{\min}$ = minimum height in satellite DEM – minimum height in DGPS.
ΔH_{mean} = mean height in satellite DEM – mean height in DGPS
$\Delta Std.dev$ = Standard deviation in satellite DEM – standard deviation in DGPS

and considering DGPS data with centimeter level accuracy in stop-n-go mode as shown in Table 5. In both cases SRTM and Cartosat-1 data have less variation in the maximum, minimum, mean height and standard deviation as shown in Table 5. It has been revealed that statistical parameters in SRTM and Cartosat-1 as compared to DGPS point to data variation in $\Delta H_m ax$, $\Delta H_m in$ and $\Delta std.dev$ as shown in Table 6 which is less compared to ASTER DEM.

Reasons for the error in the case of non-interpolation value are that it is not based on the principle of spatial autocorrelation or spatial dependence but directly uses the pixel value from the raster DEM. In the case of the interpolation method it uses the spatial autocorrelation or spatial dependence which measures degree of relationship/dependence between near and distant objects. The error in the DEM generated surface depends upon the many factors such as nature of terrain, sample density of original data, minimum spacing between sample (resolution in image) and interpolation techniques. There is no hard and fast rule of the use of interpolation techniques to be applied over data but it should produce the lowest error in generating the interpolated surface. SRTM and Cartosat-1 after applying BI over it have reduced errors because it considers the closest 2×2 neighborhood of known pixel values surrounding the unknown pixel. It then takes a weighted average of these 4 pixels to arrive at its final interpolated value. This results in much smoother looking images than the nearest neighbor. BI has produced the best result in minimal height variation outcome as compared to other interpolation methods. BI in ArcGIS is designed for image processing so this interpolation was undertaken using a purpose written program (Wise, 2011). But in the case of ASTER DEM statistical parameter variation is very high as compared to other DEMs. In this case GPI with a higher degree polynomial order of 9 had shown the best result as compared to the other interpolation methods.

Due to high error there is no high correlation coefficient between satellite DEM's and DGPS. Finding a correlation in estimated and predicated height data it has been revealed that SRTM and Cartosat-1 DEM had higher values as compared to ASTER DEM. Coefficient of correlation (R^2) SRTM and Cartosat-1 DEM is less by 0.7 and but in the case of ASTER DEM it is less by 0.3.

Table 4 Shows comparative analysis of different interpolation methods of various DEMs.

	IDW3	IDW15	GPI	MRBF	LPI	OK	UK	TR	BI
Mean error									
SRTM	1.56	1.57	1.21	1.41	1.40	−1.34	−1.35	−1.40	−0.36
Aster	0.29	0.27	0.81	0.33	0.36	0.32	0.22	0.28	0.28
Cartosat-1	3.42	3.45	3.63	3.41	3.35	3.33	3.36	−3.40	−2.74
RMSE									
SRTM	3.85	3.87	4.56	3.73	3.67	3.65	3.64	3.67	2.73
Aster	6.01	6.01	4.99	6.17	5.93	6.14	6.11	6.13	6.12
Cartosat-1	4.20	4.21	4.47	4.18	4.15	4.11	4.14	4.16	3.36

Table 5 Actual height variation in satellite DEM's and DGPS.

Height	SRTM DEM (Geoided model EGM98)	ASTER DEM (Geoided model EGM98)	Cartosat-1 DEM (Ellipsoidal height)	DGPS	
				Geoided model EGM96	Ellipsoidal height
Maximum	539	552	486	537	479.88
Minimum	517	503	461	511.362	454.262
Mean	530.90	529.01	475.02	526.99	468.68
Std. dev	4.25	6.42	3.79	4.29	

5. Conclusion

A Comparative analysis was made upon open source DEM such SRTM, ASTER and Cartosat-1 DEM for validation and performance evaluation. The following conclusions can be drawn from the present investigation

- From the analysis it is clear that Cartosat-1 DEM which is 30 m (1arc sec) resolution is better than SRTM and ASTER DEM. It had produced the lowest RMSE of 3.49 m with a ME of −2.49 m without using interpolation techniques.
- Considering DGPS data with centimeter level accuracy in stop-n-go mode. Height deviation comparison of satellite DEMs and DGPS is done. SRTM DEM has produced less deviation in statistical parameters such as $\Delta H_{\max}$, $\Delta H_{\min}$ and $\Delta std.dev$, as compared to Cartosat-1 and Aster DEM's.
- By applying various interpolation methods on a DEMs it had been found that BI methods had produced better results with less height deviation. This method can be used for SRTM and Cartosat-1 data. In our case, SRTM DEM data have produced an RMSE of 2.73 m with a mean error of −0.36 m and Cartosat-DEM data with a RMSE of 3.36 m and ME of −2.74 m. In the case of ASTER DEM, the GPI method with a higher polynomial had produced RMSE value of 4.99 m with a ME of 0.81 m.

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