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Evaluating terrain type using geoid heights obtained from different geoids in varied topographic regions with different complexity

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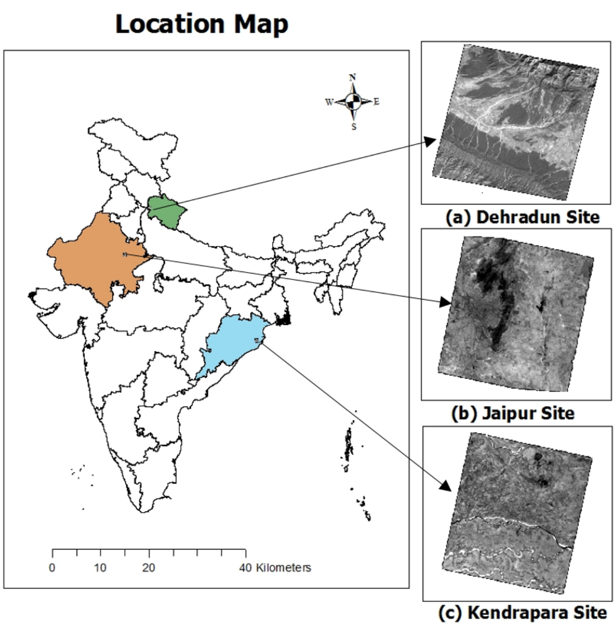
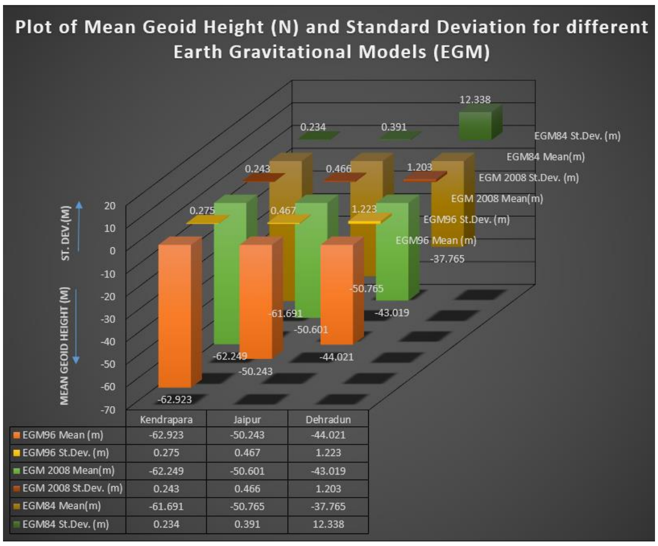
Graphical Abstract





Abstract.
Geoid heights are important for converting terrain elevation from one reference system to another. Different space agencies have developed digital elevation model (DEM) products, which are commercially as well as openly accessible for the earth or its regions in different vertical datums. These DEMs are commonly available in either EGM96 or WGS84 datum. The shape of the geoid(s) developed over time have been derived using approximation of spherical harmonics. Geoid height plays an important role during comparison, validation and utilization of these DEMs. In this study, geoid heights (N) were calculated for EGM84, EGM96 and EGM 2008 using GeographicLib online service at locations of ground control points (GCPs) and analyzed. The mean geoid undulation for the three sites at Kendrapara, Orissa; Jaipur, Rajasthan and Dehradun, Uttarakhand are -62.92m, -50.24m and -44.02m respectively. Whereas the standard deviation for the three sites at Kendrapara, Odisha; Jaipur, Rajasthan and Dehradun, Uttarakhand are 0.27m, 0.46m and 1.22m respectively. The negative values of geoid heights in all the three experimental sites depict negative gravity anomaly i.e. mass deficit, at these sites and thus indicating that in these regions the surface of the geoid is lower than the reference

	ellipsoid (WGS84). The resulting standard deviations also depict the increasing roughness of the experimental sites in the order: Kendrapara site, Jaipur site to maximum at Dehradun site.

Introduction

Currently, in this era of high resolution and very high resolution datasets, an accurate Earth geoid model representing the equipotential gravitational surface is a prerequisite for applications in cartography, photogrammetry, geophysics, and oceanography. The most popular earth gravity models used in the field of remote sensing are the Earth Gravitational Model 1996 (EGM96), and Earth Gravitational Model 2008 (EGM 2008), due to their high utilization in open source digital elevation models and other photogrammetric products. Satellite gravity missions aided significantly in the past two decades for development of several high-degree geopotential models using satellite tracking data such as those from Gravity Recovery and Climate Experiment (GRACE) and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE).The EGM96 was jointly developed by the NASA Goddard Space Flight Center (GSFC), the National Imagery and Mapping Agency (NIMA), and the Ohio State University (OSU) by including information from all available surface gravity, ocean altimeter and satellite based observation datasets . EGM96 was used to compute geoid undulations accurate to better than 1m (with the exception of areas void of dense and accurate surface gravity data) and realize WGS84 as a true 3D reference system. Later EGM2008, which is a spherical harmonic model, was developed by assimilating terrestrial, airborne and altimetry (spaceborne) gravity data. Several Preliminary Gravitational Models (PGM) were developed for evaluation in the duration of development of EGM 2008, whose details can be seen in literature (Lemoine et al., 1998; Pavlis, Holmes, Kenyon, & Factor, 2012). EGM84 with a order and degree of 180, has also been used and available in literature for comparative studies between vertical datums (Bulangas, Mohammed, & Jackson Ismaila, 2017).

The GRACE Gravity Model 01 (GGM01), computed from 111 days of GRACE K-band ranging (KBR) data, represents a dramatic improvement over older geoid models. GGM01C and GGM02C were only complete to degree 200, and were seamlessly extended using the EGM96 coefficients for degrees 201–360. Consequently, GGM02S model was determined solely from GRACE data by including observations from KBR system, high precision accelerometers (ACC) and global positioning system (GPS). Thereafter, GGM02C was prepared by the combination of the GGM02S gravity field model with terrestrial gravity information. Based on the calibrated covariances, GGM02 represents an improvement over GGM01 models by a factor greater than two (Tapley et al., 2005). The European Improved Gravity model of the Earth by New techniques (EIGEN)-6C4, also represents a high-resolution gravity models with spherical degree and order 2190 (Amin, Sjöberg, & Bagherbandi, 2019; Chang, Qin, & Wu, 2019; Greff-Lefftz, Etivier, & Legros, 2005). Although many new EGM models have been developed over time due to technological development, the EGM96 model still remains of major use among researchers due to its usage in openly accessible datasets.

Geoid Height Computation from global geopotential models (GGMs)

A spherical harmonic series can compute the geoid heights (N) at a point P required for the global gravity field analysis using Equation 1 (Bernhard, Hofmann-Wellenhof Moritz, 2005; Bulangas et al., 2017; Heiskanen, W.A.; Moritz, 1967; Kim, Yun, & Choi, 2020).

$$N(\varphi_p, \lambda_p) = R \sum_{l=2}^{L} \sum_{m=0}^{l} [(\bar{C}_{lm} \cos \lambda_p + \bar{S}_{lm} \sin \varphi_p)] \bar{P}_{lm} (sin\varphi_p) \quad (1)$$

where R is the mean radius of Earth; $\bar{C}_{lm}$ and $\bar{S}_{lm}$ are the fully normalized spherical harmonic coefficients; $\bar{P}_{lm}(sin\varphi_p)$, is the fully normalized associated Legendre function; and l and m are the degree and order, respectively.

Materials

Three experimental sites were chosen for the study. These three sites were selected in India with three different topographic characteristic (Figure 1). The first site is chosen in Uttarakhand around its capital city of Dehradun, which has a highly undulating terrain. The second site is in Jaipur city of Rajasthan which is majorly an urban area having agricultural activity around it with a moderate slope. Whereas the third site is relatively a plain area and is part of Kendrapara district in Odisha (earlier known as Orissa). The ground control points (GCPs) collected in differential GPS mode were used for calculations of Geoid heights at the location of GCPs at Dehradun site, Jaipur site and Kendrapara site with 41, 18 and 20 number of GCPs. Cartosat-1 orthoimages generated from Cartosat-1 stereo data using GCPs were used for visualization of the experimental sites (Figure 1).

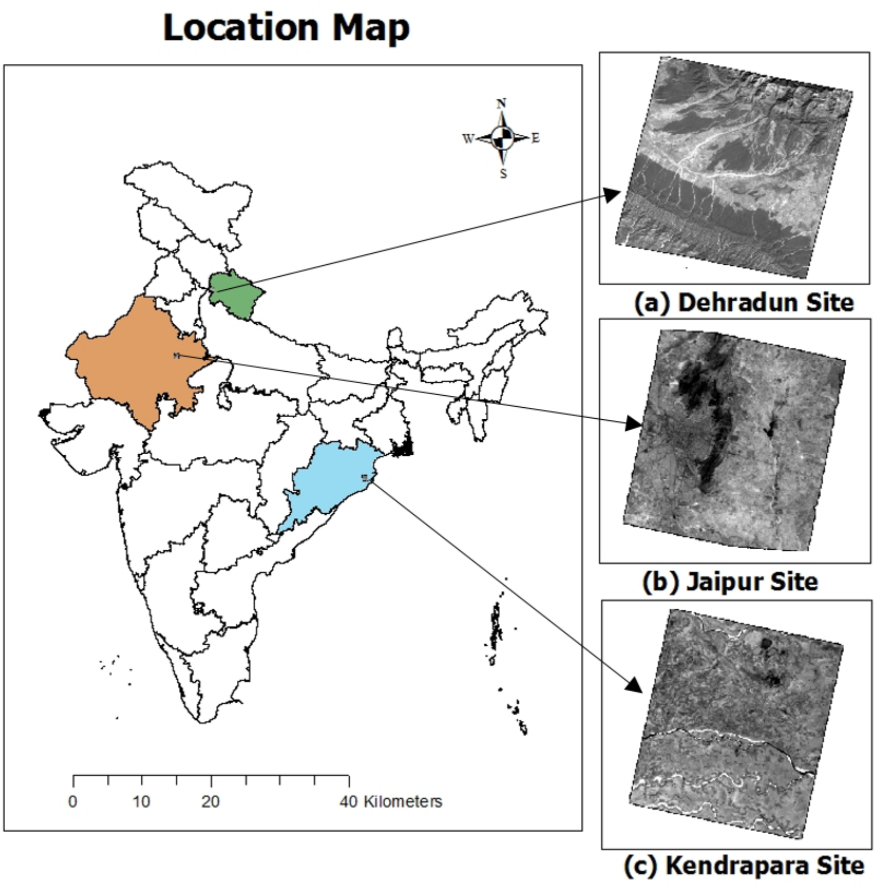


Figure 1: Location Map of three experimental sites at Dehradun, Jaipur and Kendrapara

Methods

The geoid heights at GCP locations was calculated using GeographicLib (https://geographiclib.sourceforge.io/cgi-bin/GeoidEval) online service. Similar services are available by National Geospatial-Intelligence Agency (NGIA) on their website https://earth-info.nga.mil/GandG/update/index.php?dir=wgs84&action=egm84-geoid-calc. The latitude and longitude were taken from the GCP locations to obtain the Geoid heights at those locations. The mean and standard deviations for the Geoid heights is then calculated at the GCP locations. Further equation 2 can be used for comparison of DEMs providing means to compare the DEMs in various reference systems (Bhardwaj, Jain, & Chatterjee, 2019) and other applications.

Geoid Heights (N) were calculated using GeographicLib online service with GeiodEval software utility and conversion of elevations is done using equation 2.

$$H_{EGM} = h_{GPS} - N \quad (2)$$

Where, N is the Geoid Height, h_{GPS} is the GPS elevation at the GCP location and EGM height is the elevation in the respective geoid models (EGM84, EGM96 and EGM2008) used in the study.

Results and Discussion

Mean geoid height at Kendrapara, Orissa indicates that this site is at the lowest level among the three experimental sites i.e. at -62.92m below the reference ellipsoid (WGS84), and standard deviation of 0.27m indicates a relatively plain region. Standard deviation of 0.46m refers to a moderate terrain at Jaipur, Rajasthan with medium terrain slope conditions having a mean geoid height of -50.24m. Mean and standard deviation for highly undulating terrain of Dehradun, Uttarakhand are -44.02m and 1.22m respectively. Table 1, shows significant differences exist in the undulation values (mean and standard deviations) in results obtained through EGM84 as compared to EGM96 and EGM2008 due to its geoid solution of less degree and less order of 180. Geoid height (N) is a must requirement for evaluation of a DEM (Bhardwaj, 2019; Bulangas et al., 2017; Mukherjee, Mukherjee, Garg, Bhardwaj, & Raju, 2013).

Table 1: Mean and Standard Deviation (St. Dev.) for the three experimental sites.

Experimental Site	EGM96		EGM 2008		EGM84	
	Mean (m)	**St.Dev. (m)**	**Mean(m)**	**St.Dev. (m)**	**Mean(m)**	**St.Dev. (m)**
Kendrapara	-62.923	0.275	-62.249	0.243	-61.691	0.234
Jaipur	-50.243	0.467	-50.601	0.466	-50.765	0.391
Dehradun	-44.021	1.223	-43.019	1.203	-37.765	12.338

Table1 and Figure2, depicts that the highest standard deviation of over 12m is found for Dehradun site with EGM84, and represent much more undulations due to rate of change of gravity anomaly (mass deficit) as compared to the other two sites at Jaipur, Rajasthan and Kendrapa, Odisha. However, with EGM96 and EGM 2008, it can be seen that although the standard deviations were corrected with decrease in standard deviations at 1.223m and 1.203m, the gravity anomaly is still higher at Dehradun site, when compared to the standard deviations at the other two sites at Jaipur, Rajasthan and Kendrapara, Odisha.

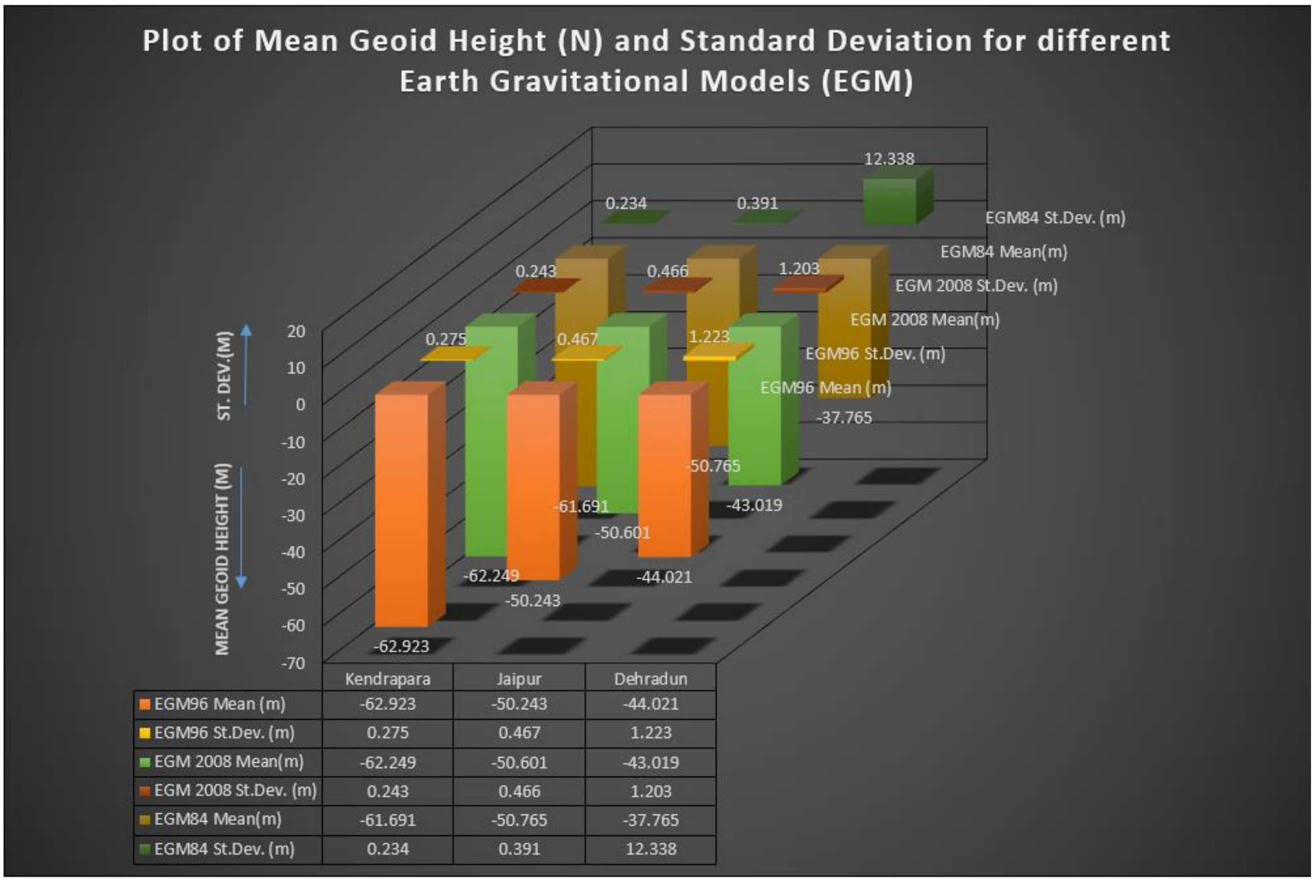


Figure 2: Plot of Mean Geoid Height (N) and St. Dev. for different Earth Gravitational Models (EGM)

The DGPS datasets used here generates overfitting statistics and thus can have better representation with inclusion of more samples (GCP locations) for calculation of geoid undulations. Assessment of EGM96 and EGM2008 models using GCPs (Sadasiva Rao, Anil Kumar, Gopala krishna, Srinivasulu, & Raghu Venkataraman, 2012), astrogeodetic techniques (Hirt, Marti, Bürki, & Featherstone, 2010) and levelling points (Falchi, Parente, & Prezioso, 2018; Kim et al., 2020) have been done by researchers, which depicts similar results. DEM and its products have been assessed for various parts of earth successfully by various researchers (Bhardwaj, 2013; Bhardwaj, Chatterjee, & Jain, 2013; Bhardwaj et al., 2019; Dowman, Jacobsen, Konecny, & Sandau, 2012; Jacobsen, Crespi, Fratarcangeli, & Giannone, 2008; Passini, Day, Weaver, & Jacobsen, 2017). Lookup tables having built-in undulations are used in memory of equipment's such as many handheld GPS receivers to determine the height above sea level, as calculating the undulations is mathematically time consuming, expensive and challenging in real time (Pavlis et al., 2012; Tapley et al., 2005).

Conclusions

The earth geoid models are an essential part of datum transformation. It is also observed that the EGM84 statistics depicts higher deviations from EGM 2008 & EGM96, especially in the undulating terrain at Dehradun site with a standard deviation of over 12m. EGM 2008 is more accurate as compared to EGM96 being at a higher degree i.e. 2160 and has slight differences with EGM 96 as shown above. However the mostly used earth geoid model is EGM96 with solution at degree as 360, due to its maximum usage in the openly accessible datasets currently.

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