Accuracy analysis of the 2014–2015 Global Shuttle Radar Topography Mission (SRTM) 1 arc-sec C-Band height model using International Global Navigation Satellite System Service (IGS) Network

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Global Shuttle Radar Topography Mission (SRTM) data products have been widely used in Earth Sciences without an estimation of their accuracy and reliability even though large outliers exist in them. The global 1 arc-sec, 30 m resolution, SRTM C-Band (C-30) data collected in February 2000 has been recently released (2014–2015) outside North America. We present the first global assessment of the vertical accuracy of C-30 data using Ground Control Points (GCPs) from the International GNSS Service (IGS) Network of high-precision static fiducial stations that define the International Terrestrial Reference Frame (ITRF). Large outliers (height error ranging from –1285 to 2306 m) were present in the C-30 dataset and 14% of the data were removed to reduce the root mean square error (RMSE) of the dataset from ~187 to 10.3 m which is close to the SRTM goal of an absolute vertical accuracy of RMSE ~10 m. Globally, for outlier-filtered data from 287 GCPs, the error or difference between IGS and SRTM heights exhibited a non-normal distribution with a mean and standard error of 6.5 ± 0.5 m. Continent-wise, only Australia, North and South America complied with the SRTM goal. At stations where all the X- and C-Band SRTM data were present, the RMSE of the outlier-filtered C-30 data was 11.7 m. However, the RMSE of outlier-included dataset where C- and X-Band data were present was ~233 m. The results suggest that the SRTM data must only be used after regional accuracy analysis and removal of outliers. If used raw, they may produce results that are statistically insignificant with RMSE in 100s of meters.

1. Introduction

The Shuttle Radar Topography Mission (SRTM) collected near-global data during the 11-day mission (Bamler 1999; Farr and Kobrick 2000; Werner 2001; Rabus *et al.* 2004) in February 2000 at a resolution of 30 m (1 arc-sec) using C- and X-Band antennae (Farr and Kobrick 2000). The X-Band data were available in 30 m resolution but with limited coverage due to the lower swath width of the X-Band

antennae. The C-Band data were released globally (except the USA, where it was released at 30 m) after re-sampling it to 90 m (3 arc-sec) resolution. However, since September 2014, the 1-arc, C-Band 30 m SRTM (C-30) data have been released in a phased manner outside USA. The C-30 data for North and South America and parts of Africa and Europe were released on September 23, 2014 followed by data from Australia and parts of Asia on January 2, 2015. The remaining C-30 data in

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the Arabian peninsula and some parts of Europe, Africa and Asia were released on August 6, 2015. It is appropriate, therefore, to now extend the Mukul Manas *et al.* (2015) methodology to assess the accuracy of the global C-30 data and explore a robust strategy for using the SRTM data products. Global SRTM Digital Terrain Elevation Data (DTED) have been widely used in Earth Sciences but are typically used ignoring errors that can affect results (Wechsler 2003) even though several studies have indicated that large outliers exist in the Shuttle Radar Topography Mission (SRTM) data products (e.g., Rodriguez *et al.* 2005; Mouratidis *et al.* 2010; Kolečka and Kozak 2014). In this study we use the high-precision GCPs of the International GNSS Service (IGS) Network (Dow *et al.* 2009) to answer the following questions related to the accuracy of C-30 data compared to the targeted SRTM vertical accuracy of RMSE of ~ 10 m (and not 16 m, e.g., Varga and Tomisla 2015) corresponding to a linear error at 90% confidence (LE90) of 16 m (Rabus *et al.* 2004; USGS 2005; Farr *et al.* 2007; JPL 2009):

1. What is the vertical accuracy of the 1-arc C-Band 30 m resolution SRTM data using GCPs from the International GNSS Service (IGS) Network of high-precision static fiducial stations that define the International Terrestrial Reference Frame (ITRF) IGS Network?
2. How does the vertical accuracy of 1-arc C-Band 30 m data compare with the accuracy of 1-arc X-Band 30 m and 3-arc C-Band 90 m data? Is there a marked improvement in the vertical accuracy of the 1-arc C-Band 30 m SRTM data over previously released datasets?
3. What is the strategy to follow while using SRTM data products? Can we really use raw SRTM products without worrying about uncertainties involved?

2. Methodology

This study is an extension of Mukul Manas *et al.*'s (2015) study carried out for the 3-arc C-Band 90 m resolution C-90 data (C-90) and, therefore, we have followed the identical methodology and described issues relevant only to the C-30 data below. The global IGS stations have been used as GCPs in this study just like in Mukul Manas *et al.* (2015).

2.1 Obtaining IGS GCPs

A total of 427 stations exist in the IGS Network (Supplementary data) out of which only 335 stations were usable as some stations were out of the SRTM zone (latitude greater than 60°N and 57°S).

The statistical analysis, therefore, was done with these 335 IGS GCPs (figure 1a). The C-90 study was carried out with 334 IGS GCPs (Mukul Manas *et al.* 2015).

2.2 Obtaining C-Band 30 m resolution data

The void-filled, C-30 data were available at the US Geological Survey website and were downloaded from the USGS Earth Explorer Interface in GeoTiff format. The GCPs were superimposed over these GeoTiff files in ArcGIS and the corresponding EGM96 (orthometric) heights of the 30 m C-Band SRTM points were extracted. Geoidal separations were added to the orthometric heights to convert them to ellipsoidal heights for comparison with the ellipsoidal heights of the GCPs following the methodology outlined in Mukul Manas *et al.* (2015).

2.3 Statistical analysis

The C-30 heights were subtracted from the IGS GCP heights to obtain the error at each of the 335 IGS locations. The dataset was subjected to normality tests to compute the appropriate statistical measure (LE90 or RMSE) for comparison of results with other datasets. The stem-and-leaf method (figure 2) was used to identify outliers or locations with very high errors. For 48 out of the 335 GCPs, errors were between -1285 and 2306 m; these were filtered as outliers (figure 1b). Bogota, Colombia, at elevation 2576.8 m, had the highest error of 2305.9 m. These outliers resulted from errors in measurement, collection or interpolation of data and caused inflation of errors (Zimmerman 1994, 1995, 1998). There were 20 outlier GCPs common to the 3-arc C-Band 90 m resolution (C-90), 1-arc C-Band 30 m resolution (C-30) and 1-arc X-Band 30 m resolution (X-30) datasets (tables 1 and 2). The outliers were also analysed against the elevation of the IGS station and the errors were found to increase with station elevation (figure 3). On removal of the outliers the errors were uniformly distributed (figure 4).

The complete dataset (335 GCPs) and the outlier-filtered dataset (287 GCPs) were subjected to statistical analysis and mean error (ME), standard deviation (SD), standard error of mean (SEM), mean absolute error (MAE) and root mean square error (RMSE) were computed. The outlier-filtered dataset was separated into continents and the results were compared to the previously published results (Rodriguez *et al.* 2005, 2006; Mukul Manas *et al.* 2015). The main objective of doing the statistical analysis was to extend the Mukul Manas *et al.* (2015) analysis by comparing the results of the C-30 data to that from C-90 and X-30 data.

Figure 1. (a) Map showing the distribution of 335 IGS GCPs used to assess the vertical accuracy of the global 1-arc, 30 m resolution, C-Band SRTM dataset. (b) Map showing the distribution of 48 C-30 outliers with their corresponding station numbers.

3. Results

3.1 The global C-Band 30 m dataset

The statistical analysis for the C-30 global data was done with both the outlier-filtered and outlier-included datasets consisting of 287 and 335 GCPs (table 2). The normality tests failed for both the datasets. The outlier-included data had skewness of

6.46 (standard error = 0.13) and kurtosis of 89.17 (standard error = 0.27) whereas the skewness and kurtosis of outlier-filtered data was 0.52 (standard error = 0.14) and 0.84 (standard error = 0.29) respectively. The Shapiro–Wilk’s ($p > 0.05$) (Shapiro and Wilk 1965; Razali and Wah 2011) normality test also failed with $p = 0.00$ for both the datasets. Therefore, as the C-30 dataset failed the normality test, the RMSE (and not LE90) is the appropriate

Figure 3. Plot of C-Band 30 m absolute error magnitude with increasing IGS elevation for the outliers.

Figure 4. Plot showing C-Band 30 m outlier-filtered absolute errors with increasing elevation of the IGS stations. Outliers and errors are higher at higher elevations.

Table 2. Results of the statistical analysis of global SRTM data for both the outlier-included and outlier-filtered datasets.

Datasets	Outlier-included			Outlier-filtered		
	C-90	C-30	X-30	C-90	C-30	X-30
Total stations considered	334	335	156	290	287	135
Mean error (ME) [m]	32	20.4	34.2	6.9	6.5	8.2
Mean absolute error (MAE) [m]	51	40.7	48.4	7.8	7.8	8.8
Root mean square error (RMSE) [m]	274.5	186.5	232.6	10.3	10.3	11.5
Standard deviation (SD) [m]	273.5	185.7	230.8	7.8	8.1	8.1
Standard error (SEM) [m]	15	10.2	18.5	0.5	0.5	0.7
Total number of outlier stations	44	48	21	–	–	–

all the datasets, the ME and MAE of the three datasets improved to ~ 8 and ~ 9 m, respectively. The RMSE for the three datasets were ~ 11.5 m. The SD and SE were ~ 9 and 0.8 m respectively.

3.3 Continental dataset

In order to compare the C-30 outlier-filtered results with earlier global studies (Rodriguez *et al.* 2005;

Figure 5. Plot showing a positive bias for the outlier filtered C-Band 30m errors for all the IGS stations.

Table 3. Results of the coincident C-90, C-30 and X-30 data.

Common GCPs Datasets	Outlier-included			Outlier-filtered		
	C-90	C-30	X-30	C-90	C-30	X-30
No. of points	155	155	155	131	133	134
Mean error [m]	34.5	34.0	34.4	8.0	7.7	8.2
Mean absolute error (MAE) [m]	48.9	48.7	48.7	8.8	9.1	8.9
Standard deviation (SD) [m]	230.9	231.0	231.5	8.3	8.9	8.1
Standard error (SEM) [m]	18.6	18.6	18.6	0.7	0.8	0.7
Root mean square error (RMSE) [m]	232.7	232.8	233.3	11.5	11.7	11.5

Mukul Manas *et al.* 2015), the global dataset was separated into continents (Supplementary data). The continent-wise results for the C-30 data are shown in table 4. The ME of the continents ranged from 3 (Australia) to 8.5 m (Asia). The SD for all the continents were between 4.5 and 10 m, with the lowest value of 4.6 m from the Island dataset and highest 9.8 m from Africa. The SEM ranged from 0.7 (Eurasia) to 2.6 m (Africa). The MAE of the continents ranged between 3.5 (Australia) and 9.4 m (Europe and Asia).

The RMSE of Asia (12.1 m), Europe (11.9 m) and Africa (10.3 m) were marginally higher than the SRTM RMSE goal of ~ 10 m. Australia, N. America, S. America and the Island dataset complied with the SRTM goal with RMSEs of 5.9, 8.7, 9.7 and 5.7 m, respectively. Eurasia, consisting of a combined dataset of 139 GCPs from Asia and Europe, returned a ME of 8.4 m, SD of 8.6 m and SEM of 0.7 m. The MAE and RMSE of Eurasia were 9.4 and 12 m, respectively.

4. Discussion

The Global SRTM DTED are being used without considering errors, outliers or any accuracy estimation (Wechsler 2003). Our analysis of C-30 (tables 1 and 2) as well as C-90 and X-30 (Mukul Manas *et al.* 2015) data have pointed to significant errors and presence of outliers in all the SRTM datasets. The largest outliers for C-90 and X-30 were obtained at Mauna Kea, USA (3687 m) and Bogota, Colombia (2309.8 m) respectively. Bogota, Colombia (2305.9 m) is also the largest outlier for C-30. Such large outliers increase the RMSE for SRTM data by an order of magnitude over the SRTM goal of RMSE ~ 10 m. For example, outlier-included data for the C-30 dataset has a RMSE of ~ 187 m for global data which is lower than that of the C-90 (274.5 m) and X-30 (232.6 m) datasets (table 2). This is further supported by the C-90, C-30 and X-30 RMSEs of ~ 233 m respectively computed from GCPs with coincident X- and C-Band data (table 3). Most

Table 4. Continent-wise result of the statistical analysis of C-Band outlier-filtered 30 m SRTM data.

Statistics of continent-wise data Datasets	Africa			Asia			Australia			Europe			Eurasia			Island			N. America			S. America		
	C-90	C-30	X-30	C-90	C-30	X-30	C-90	C-30	X-30	C-90	C-30	X-30	C-90	C-30	X-30	C-90	C-30	X-30	C-90	C-30	X-30	C-90	C-30	X-30
Total stations considered	23	14	8	48	51	32	24	24	16	88	88	39	136	139	71	11	11	2	72	75	27	24	24	11
Mean error (ME) [m]	4.0	4.0	5.7	8.0	8.5	11.3	3.7	3.0	5.8	9.4	8.3	10.4	8.9	8.4	10.8	2.9	3.6	6.1	6.1	5.6	3.6	5.2	4.1	8.0
Mean absolute error (MAE) [m]	5.6	9.0	5.7	8.8	9.4	11.4	4.5	3.5	5.9	9.8	9.4	10.7	9.4	9.4	11.0	3.6	4.3	6.1	7.1	6.7	5.7	7.7	7.2	9.3
Root mean square error (RMSE) [m]	7.9	10.3	7.0	11.0	12.1	14.2	6.9	5.9	7.6	12.4	11.9	13.4	11.9	12.0	13.8	5.0	5.7	6.1	9.0	8.7	7.3	11.2	9.7	11.5
Standard deviation (SD) [m]	7.0	9.8	4.5	6.7	8.7	8.8	6.0	5.2	5.0	8.2	8.6	8.6	8.0	8.6	8.6	4.3	4.6	0.4	6.6	6.7	6.4	10.2	9.0	8.6
Standard error (SEM) [m]	1.5	2.6	1.6	1.0	1.2	1.4	1.2	1.1	1.3	0.9	0.9	1.4	0.7	0.7	1.0	1.3	1.4	0.3	0.8	0.8	1.2	2.1	1.8	2.6

of the high errors were from the high elevation regions (figure 3). Therefore, as the vertical accuracies of all the outlier-included datasets are an order of magnitude higher than the SRTM goal, it is inaccurate to use raw SRTM datasets, particularly in higher elevations, as they will give statistically insignificant results. Removal of outliers before use of all SRTM data is absolutely essential to get the SRTM datasets close to the SRTM RMSE goal of ~ 10 m as well as for statistically meaningful results. This is evident from the analysis of the global dataset (table 2) where outlier-filtered C-30, C-90 and X-30 dataset have RMSE ~ 10 – 11.5 m. Also, GCPs with coincident X-30, C-30 and C-90 datasets have RMSE of ~ 11.5 m (table 3). It is also evident that C-Band data have lower RMSE of 10.3 m than that of X-30 data (RMSE 11.5 m) for the global dataset.

The results of the C-30 dataset were also compared with the C-90 and X-30 datasets after separating the global dataset into continental datasets (Rodriguez *et al.* 2005, 2006; Mukul Manas *et al.* 2015) (table 4). The RMSEs of C-30 data for Africa, Asia, Eurasia and the Island dataset were higher than the RMSEs of C-90 data. The X-30 RMSE was lower than C-30 and C-90 RMSEs in Africa and North America (table 4). The C-30 data RMSEs were lower than that for C-90 and X-30 data for Australia, Europe and S. America. For Asia, Eurasia and the Islands, the RMSEs for C-30 data were lower than that of the X-30 data but higher than the C-90 data. The difference between the RMSE of C-Band 30 m and X-Band 30 m were in the range between 1.0 and 2.5 m for Australia, Europe, Asia, N. America and S. America. The highest variation (3.3 m) of the RMSE was in Africa (table 4). The C-30 RMSE results, however, were much higher than the Rodriguez *et al.*'s (2005) RMSE results (table 5). The RMSE of all the continents of the Rodriguez *et al.* (2005) study complied with the SRTM goal with values in the range between 3.4 and 5.5 m. However, only Australia, N. America, S. America and the Island dataset complied with the SRTM goal of RMSE ~ 10 m for the C-30 data (tables 4 and 5).

The mean errors for all the SRTM data were positive, indicating a bias which could be corrected to improve the vertical accuracy of the SRTM heights. A single pixel of 90 m resolution has the same elevation (x) (figure 6) for a region covering 8100 m^2 , where as a single pixel of 30 m resolution has the same elevation for a region of 900 m^2 . Hence, the C-30 data should be more accurate as nine different elevation values ($x_1, x_2, \dots, x_9$) are available (figure 6) in C-30 for a single C-90 pixel for the same 8100 m^2 . The RMSEs of C-30 global data are seen to be within SRTM RMSE goal only for the Australian, Island and N. and S. American continents.

Table 5. Comparison of RMSEs of C-Band 30 m resolution data with C-Band 90 m data from Mukul Manas *et al.* (2015) and Rodriguez *et al.* (2005) and X-Band 30 m SRTM from Mukul Manas *et al.*'s (2015) study.

Datasets			C-Band 90 m RMSE (m)	X-Band 30 m RMSE (m)	C-Band 30 m RMSE (m)
Global	LE90 (m)	Computed RMSE (m)	10.3	11.5	10.3
Africa	5.6	3.4	7.9	7	10.3
Australia	6	3.7	6.9	7.6	5.9
Asia	—	—	11	14.2	12.1
Europe	—	—	12.4	13.4	11.9
Eurasia	6.2	3.8	11.9	13.8	12.0
Islands	8	4.9	5	6.1	5.7
N. America	9	5.5	9	7.3	8.7
S. America	6.2	3.8	11.2	11.5	9.7

Figure 6. Diagram indicating the differences between the pixels belonging to 90 m and 30 m resolution SRTM data. A single pixel from a 90 m resolution data has a single elevation value, indicated by 'x' whereas for the same area, the 30 m offers 9 pixel with separate elevation values indicated by 'x1, x2, x3, ..., x9'.

Therefore, accuracy analysis of SRTM data with denser GCPs (e.g., Rodriguez *et al.* 2005) but with better spatial distribution (e.g., Mukul Manas *et al.* 2015) is required to assess the differences in the quality of C-90, X-30 and C-30 SRTM data in continents better. Meanwhile, our present work along with Mukul Manas *et al.* (2015) clearly demonstrates the severe problems associated with using raw SRTM data without the removal of outliers and analysis of errors.

5. Conclusions

1. A global assessment of the recently released 1-arc, 30 m resolution, C-Band SRTM dataset using the GCPs from the global IGS Network (table 5) reveals that it has the same accuracy and RMSE (10.3 m) as the 3-arc, 90 m resolution C-Band data. However, it is more accurate than the 30 m resolution, X-Band (11.5 m) SRTM data. The RMSEs of all the datasets are marginally higher than the SRTM RMSE goal of ~ 10 m.
2. Accuracy analysis of STRM data from GCPs with coincident C-30, C-90 and X-30 data (table 3) indicate that outlier-filtering reduces the RMSEs of the datasets from ~ 233 to ~ 11.5 m. The accuracies of the three datasets are almost identical. Also the errors in the C-30 increase with the increase in elevation.
3. When the global dataset is divided into continents, only the 1-arc, 30 m resolution, C-Band SRTM dataset from Australia, N. America, S. America and the Island dataset comply with the SRTM RMSE goal of ~ 10 m (table 4). The RMSEs of Australia, Europe, N. America and S. America for C-30 data are lower than the RMSEs of C-90 data whereas for Africa, Asia and the Island dataset the C-Band 90 m data has higher accuracy. Except Africa and N. America, the RMSEs of C-30 m data are lower than the X-Band 30 m data for all other datasets.
4. All SRTM products have outliers corresponding to high errors between the GCP and the SRTM heights especially at high elevations. Therefore, raw SRTM products cannot be used without

assessing their uncertainties and removal of outliers. The mean errors of all SRTM datasets are positive for the global as well as continental datasets and hence correction of the positive bias can improve the accuracy of the SRTM dataset.

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