Available online at www.sciencedirect.com

ScienceDirect

Remote Sensing of Environment 104 (2006) 409 – 415

Remote Sensing of Environment

www.elsevier.com/locate/rse

Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics

Y. Gorokhovich [a],*, A. Voustianiouk [b]

[a] *Center for International Earth Science Information Network (CIESIN), Columbia University, 61 Rt 9W, PO Box 1000, Palisades, NY 10964, USA*
[b] *ANS Laboratory, Department of Neurology, Mount Sinai School of Medicine, 1 Gustave L. Levy Place, Box 1052, New York, NY 10029, USA*

Received 2 February 2006; received in revised form 23 May 2006; accepted 23 May 2006

Abstract

Shuttle radar topographic mission (SRTM) has created an unparalleled data set of global elevations that is freely available for modeling and environmental applications. The global availability (almost 80% of the Earth surface) of SRTM data provides baseline information for many types of the worldwide research. The processed SRTM 90 m digital elevation model (DEM) for the entire globe was compiled by Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) and made available to the public via internet mapping interface. This product presents a great value for scientists dealing with terrain analysis, thanks to its easy download procedure and ready-to-use format. However, overall assessment of the accuracy of this product requires additional regional studies involving ground truth control and accuracy verification methods with higher level of precision, such as the global positioning system (GPS).

The study presented in this paper is based on two independent datasets collected with the same GPS system in Catskill Mountains (New York, USA) and Phuket (Thailand). Both datasets were corrected with differential base station data. Statistical analysis included estimation of absolute errors and multiple regression analysis with slope and aspect variables. Data were analyzed for each location separately and in combination. Differences in terrain and geographical location allowed independent interpretation of results.

The results of this study showed that absolute average vertical errors from CGIAR dataset can range from 7.58±0.60 m in Phuket to 4.07±0.47 m in Catskills (mean±S.E.M.). This is significantly better than a standard SRTM accuracy value indicated in its specification (i.e. 16 m). The error values have strong correlation with slope and certain aspect values. Taking into account slope and aspect considerably improved the accuracy of the CGIAR DEM product for terrain with slope values greater than 10°; however, for the terrain with slope values less than 10°, this improvement was found to be negligible.

Keywords: SRTM; CGIAR DEM; Topography; Comparison; Elevation; GIS; Statistics; Terrain

1. Introduction

SRTM data were collected during 11-day mission in February 2000. Since then, they were described in details (Farr and Kobrick, 2000; Rabus et al., 2003; Werner, 2001) and became accessible for free download over the Internet (e.g. at ftp://e0srp01u.ecs.nasa.gov and http://seamless.usgs.gov/). However, between two SRTM products that include raster data with 30 and 90 m spatial resolution, only 90 m data is available globally (80% of the Earth surface) while the 30 m data are available only for the USA territory.

Since SRTM data became widely available, many studies utilized them for applications in topography (Falorni et al., 2005; Koch & 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 (Jarvis et al., 2004; Muller, 2005; Smith & Sandwell, 2003).

Because SRTM data produced a number of voids due to lack of contrast in the radar image, a methodology based on

---

* Corresponding author.
E-mail address: ygorokho@ciesin.columbia.edu (Y. Gorokhovich).

0034-4257/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2006.05.012

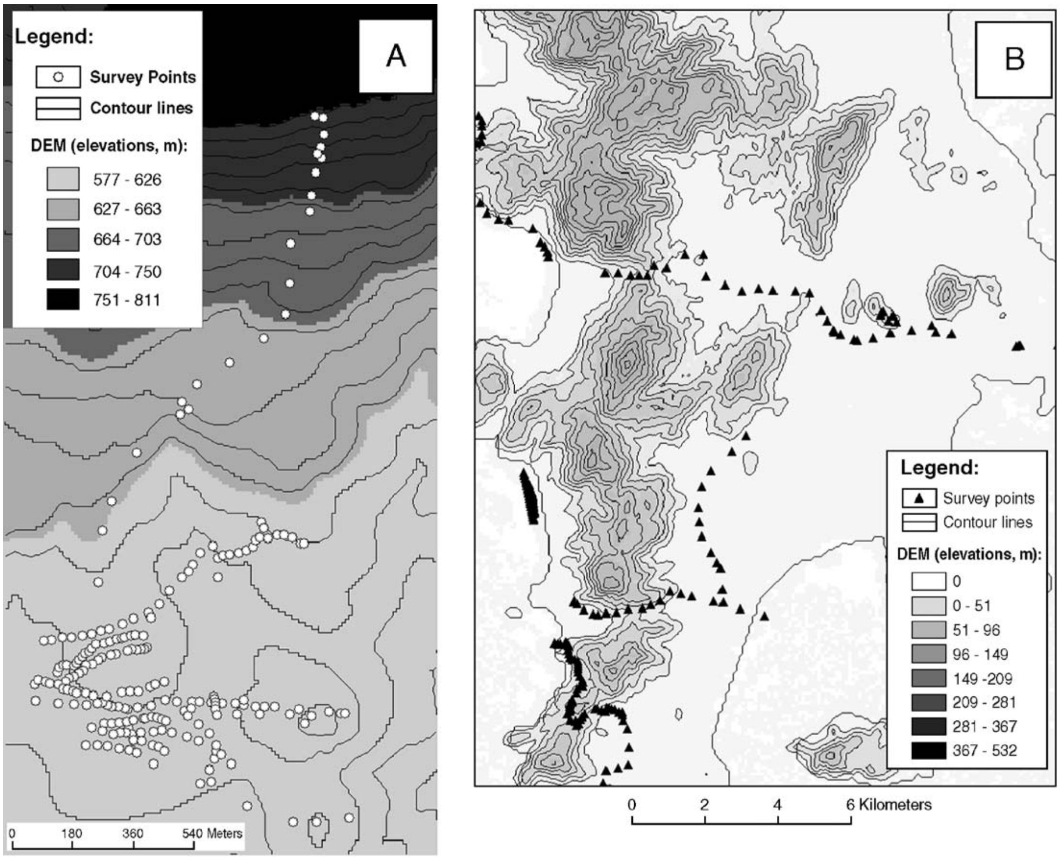

Fig. 1. Study areas in Catskills, USA (A) and Phuket, Thailand (B).

spatial filtering was developed to correct this phenomenon (Dowding et al., 2004; Jarvis et al., 2004). The final seamless dataset with voids filled in is available at the website of Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) via http://srtm.csi.cgiar.org/. Dataset compiled by CGIAR-CSI has the following advantages:

1. Dataset is seamless.
2. There is user-friendly interface for downloading specific DEM areas of interest.
3. Data are already pre-processed for the immediate use.
4. Data are available in GeoTiff format that is accepted by most GIS applications.
5. The website is supported by extensive documentation describing the process of filling voids in SRTM product.

These advantages make CGIAR-CSI SRTM data product a very valuable resource, especially for cases when analysis of terrain had to be done promptly, for example, during Asian Tsunami of 2004 (Blumberg et al., 2005). However, the accuracy of this product is yet to be assessed. Partial assessment of its accuracy was done by the Centro Internacional de Agricultura Tropical (CIAT) in South America to verify performance of the developed DEM (Jarvis et al., 2004), but global user community would gain more benefits from other regional assessments.

This study is designed to assess CGIAR DEM accuracy by comparing elevation values from processed CGIAR-CSI SRTM with elevation values collected by differential GPS system in two different geographical localities. Both datasets are based on the same vertical datum (WGS84).

2. Study areas characteristics

Elevation data in this study were collected in two geographically independent regions: Catskill Mountains (New York, USA) and Phuket (Thailand). Catskill area was surveyed in November

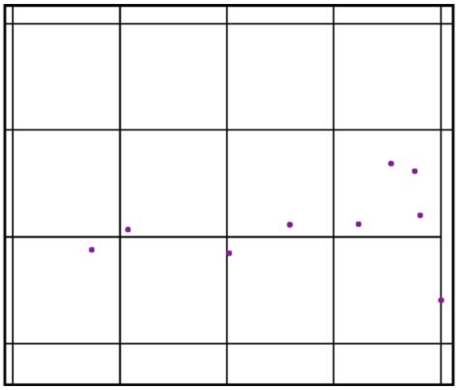

Fig. 2. GPS data (points) and SRTM pixels (squares).

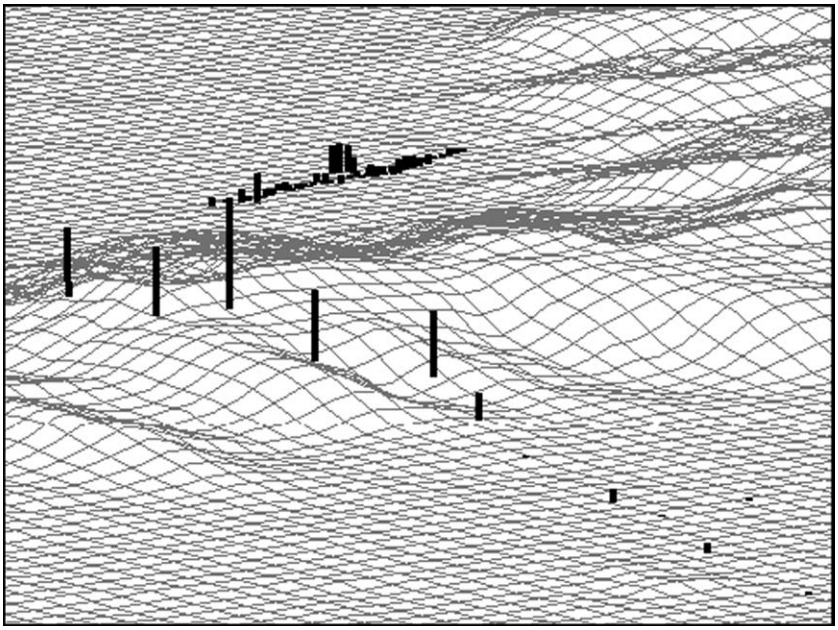

Fig. 3. Vertical errors across terrain (Phuket).

1999 and Phuket was surveyed in May 2005. Both surveys were performed with the same unit, Trimble ProXR, with real-time differential mode. After collection, data were corrected using information from local base stations.

Study area in Catskill Mountains covers slopes with elevations 577–811 m above mean sea level (Fig. 1A). Study area in Thailand covers hills, coastal plains, and bays with elevations ranging from 0 to 532 m (Fig. 1B). Both areas are covered with bush and forest type vegetation up to 10 m high.

There are some differences in covered terrain characteristics. In Thailand survey area, elevations, slopes, and aspects were more variable than in Catskill Mountains. In Catskill Mountains study area, survey covered mainly south–southwestern slope of the mountain and its lower part. Number of GPS readings per one CGIAR-CSI SRTM spatial unit (90 × 90 m) is compatible in both Thailand and Catskill Mountains areas, ranging from one to nine.

3. Methodology

3.1. GPS settings and surveying

Among various methods of accuracy assessment, GPS survey provides the best way to map features on terrain with high accuracy. In this study, GPS data were collected along roads and passable trails with Trimble ProXR receiver. It collects data using 12 channels, L1 frequency (1575.42 MHz), CA code (Coarse Acquisition Code for modulating L1 frequency), real-time receiver, and integrated beacon. These settings allow collecting high-accuracy signals into a data logger connected with the receiver (Trimble Navigation Ltd., 2004).

When surveying with GPS, the highest possible accuracy of collected data is usually achieved by using a carrier-phase tracking mode (Blomenhofer et al., 1994; Farrell et al., 2003). Because of its accuracy, this methodology is also used in tracking industry (Farrell et al., 1999) and optics (Shelton et al., 2002). This mode requires both receivers (remote and reference) to be close enough and maintain tracking carrier phases simultaneously. This limitation might slow down the process of data collection (if remote and reference devices get disconnected) and decrease battery life (waiting for establishing connection and phase carrier mode). Therefore, an alternative is to use post-processing of GPS data with available base station data. This method was used in present study.

Base station data are usually collected by a high end receiver that constantly logs coordinates of its own location and determines an error associated with the satellite position, atmospheric conditions, etc. The base station used in Phuket survey was available at Khon Kaen University in Thailand (http://negistda.

Table 1
Analysis of SRTM and GPS data for Phuket study area

Statistical parameters	SRTM data	GPS data
Mean	47.04	46.54
S.E.M.	3.41	3.32
Minimum	0	3.34
Maximum	183	190.53
Count	182	182
p value (independent measures *t*-test: SRTM vs. GPS)		0.917

Table 2
Analysis of SRTM and GPS data for the Catskill Mountains study area

Statistical parameters	SRTM data	GPS data
Mean	637.45	634.68
S.E.M.	5.28	5.12
Minimum	606	603.05
Maximum	775	773.97
Count	73	73
p value (independent measures *t*-test: SRTM vs. GPS)		0.707

Table 3
Analysis of discrepancies (absolute values) between SRTM and GPS data for Phuket and Catskill Mountains study areas

Statistical parameters	Phuket area	Catskills area
Mean	7.58	4.07
S.E.M.	0.60	0.47
Minimum	0.01	0.10
Maximum	43.21	21.88
Count	182	73
p value (independent measures *t*-test: SRTM vs. 16)	<0.0001	<0.0001

kku.ac.th/gps/gpsen.html). Data from the base station were downloaded and then used for post-processing with Trimble Pathfinder software. Base station in Catskill survey was located at Lamont-Doherty Earth Observatory, Palisades, NY.

3.2. GIS analysis

Fusion of SRTM-based elevation data from CGIAR-CSI SRTM and GPS data required overlay of two different topological objects: raster pixels and point data. This required converting both data formats into one compatible form. In the present study, CGIAR-CSI SRTM data were converted into a regular polygon dataset with attribute table storing elevation values. Thus, each polygon replicated raster pixel and was overlain with point data from GPS. This operation is also known as “spatial join”. It transfers attribute table values from polygons to underlying point data. Fig. 2 shows an example of both datasets.

Visualization of vertical errors in GIS revealed lack of uniform distribution of the errors across terrain. Fig. 3 shows an example of a survey profile in Phuket study area with elevation errors expressed as vertical bars of different height. Greater error values were associated with rugged terrain, while smaller error values were associated with coastal plain, suggesting that such terrain characteristics as slope and aspect can influence CGIAR-CSI SRTM accuracy. The effect of slope on SRTM accuracy was also investigated by Sun et al. (2003) and the influence of aspect was described by Miliaresis and Paraschou (2005).

Therefore, CGIAR-CSI SRTM data were converted into SLOPE and ASPECT grids using Arc/Info method. In this study, ASPECT grid was created using ArcInfo method (ESRI, 2005) where it is identified as “the down-slope direction of the maximum rate of change in value from each cell to its neighbors”. SLOPE grid was also created using ArcInfo method (ESRI, 2005) where it is identified as “the maximum rate of change in value from each cell to its neighbors”, using methodology described in Burrough (1986). Then both grids were overlaid with GPS survey points using “spatial join”. Thus, GPS points acquired attributes of SLOPE, ASPECT and SRTM data. All data points with their respective attributes were organized in a spreadsheet table for subsequent statistical analysis.

3.3. Statistical analysis

The main goal of statistical analysis was to answer the following questions:

1. Does absolute vertical accuracy of CGIAR-CSI SRTM data exceed the 16 m value specified for the original SRTM dataset (Rodriguez et al., 2005)?
2. How do slope and aspect influence CGIAR-CSI SRTM data accuracy?
3. Is it possible to increase the accuracy of CGIAR-CSI SRTM data using slope and aspect information?

To address these questions, we examined the magnitude of absolute errors in CGIAR-CSI SRTM data. “Errors” were operationally defined as discrepancies between elevation from CGIAR-CSI SRTM data and corresponding GPS measurements which we assumed to be accurate and, thus, used them as reference values. We averaged GPS measurements for each CGIAR-CSI SRTM spatial unit (rather than using individual GPS data) in order to avoid artificial and potentially misleading increase in the sample size. We also analyzed the magnitude of absolute errors in the CGIAR-CSI SRTM data with respect to slope and aspect characteristics of the landscape. Finally, we considered predictive value of CGIAR-CSI SRTM data for estimates of terrain elevation and whether the accuracy of predictions can be improved on the basis of available information regarding slope and aspect characteristics of the landscape. To this effect, we conducted linear regression analysis on CGIAR-CSI SRTM and GPS data and compared the results with multiple linear regression using GPS data as dependent

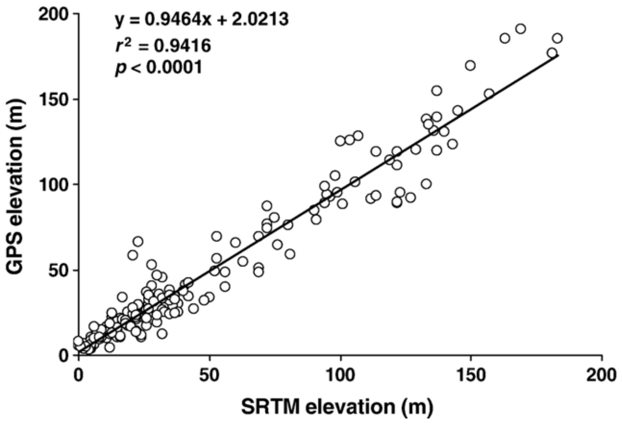

Fig. 4. Correlation between SRTM and GPS data for Phuket study area.

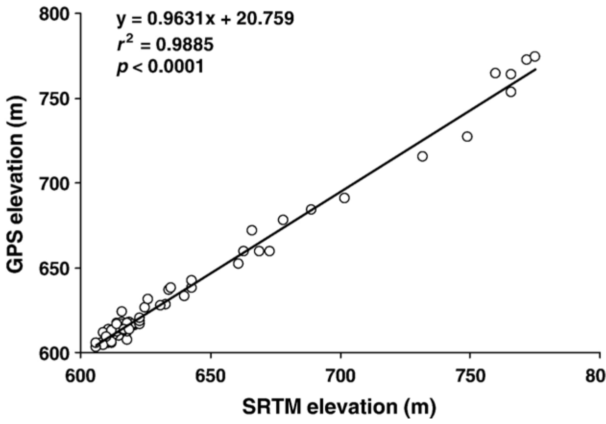

Fig. 5. Correlation between SRTM and GPS data for the Catskills study area.

Table 4
Analysis of discrepancies (absolute values) between SRTM and GPS data for terrains with slope values less and greater than 10° in Phuket and Catskill Mountains study areas

Study area	Phuket		Catskills	
Slope	≤10°	>10°	≤10°	>10°
(Mean±S.E.M.)	(3.84± 0.27)	(14.19± 0.43)	(3.49± 0.28)	(13.10± 0.20)
Mean	5.03	12.37	3.83	19.20
S.E.M.	0.41	1.31	0.35	2.70
Minimum	0.00	0.20	0.10	16.50
Maximum	21.0	43.20	13.70	21.90
Count	117	65	71	2
p value (independent measures t-test, slope ≤10 vs. slope >10)	<0.0001		<0.0001	

variable, and CGIAR-CSI SRTM, slope, and aspect data as independent variables. All analyses were performed using SPSS statistical package (ver. 13.0, SPSS Inc., Chicago, IL). In all tests, results with probability values less than 0.05 were considered statistically significant. Presented data are shown as mean±S.E.M. (standard error of the mean), unless otherwise noted.

The results of analysis can be applied to CGIAR-CSI SRTM data as "regional regression model", similar to ones, developed by USGS and USACE for flood prediction in USA. Floods "regression models" were developed for gauged streams to provide estimates of floods for ungauged sites without observations. The program started in 1993 as National Flood Frequency (NFF) program (Jennings et al., 1994). The NFF program is based on constant updating of regression equations developed for most of the USA. Since CGIAR-CSI SRTM data are available worldwide and it is hard to obtain specific field verification data everywhere, use of developed and updated regression curves in various regions can become a practical tool for CGIAR-CSI SRTM applications in applied science.

4. Results

4.1. CGIAR-CSI SRTM data accuracy

Tables 1 and 2 show descriptive statistics for CGIAR-CSI SRTM and GPS data for Phuket and Catskill areas. Results of t-tests confirm lack of significant differences between data obtained by the two methods in either study area. Table 3 summarizes discrepancies between CGIAR-CSI SRTM and GPS measurements for Phuket and Catskill Mountains study areas. Average absolute error of CGIAR-CSI SRTM data was found to be 7.58±0.60 m (Phuket) and 4.07±0.47 m (Catskills).

Linear regression analysis reveals strong correlation between CGIAR-CSI SRTM and GPS data for both Phuket (Fig. 4) and Catskill Mountains study areas (Fig. 5). ANOVA tests, performed on the linear regression data, showed this correlation to be highly significant for both study areas ($p<0.0001$ in both cases). It is of interest to note that in both cases the value of the slope of the regression line was very close to 1.

4.2. Slope and aspect influence on CGIAR-CSI SRTM data accuracy

Analysis revealed significant decrease in accuracy of CGIAR-CSI SRTM data when measurements were performed on terrain characterized by slope values greater than 10° (Table 4). Indeed, the average magnitude of errors is more than two times higher for terrains with slope values exceeding 10° compared to areas where slope values are less than 10° in Phuket study area (5.03±0.41 m vs. 12.37±1.31 m, $p<0.001$) and more than five times higher in Catskills (3.83±0.35 m vs. 19.20±2.70 m, $p<0.001$). It should be noted, though, that in the Catskills study area only two sites studied were characterized by slope values higher than 10°.

When predictive value of CGIAR-CSI SRTM elevations was considered, exclusion of data corresponding to terrains with slope values exceeding 10° from regression analysis reduced the

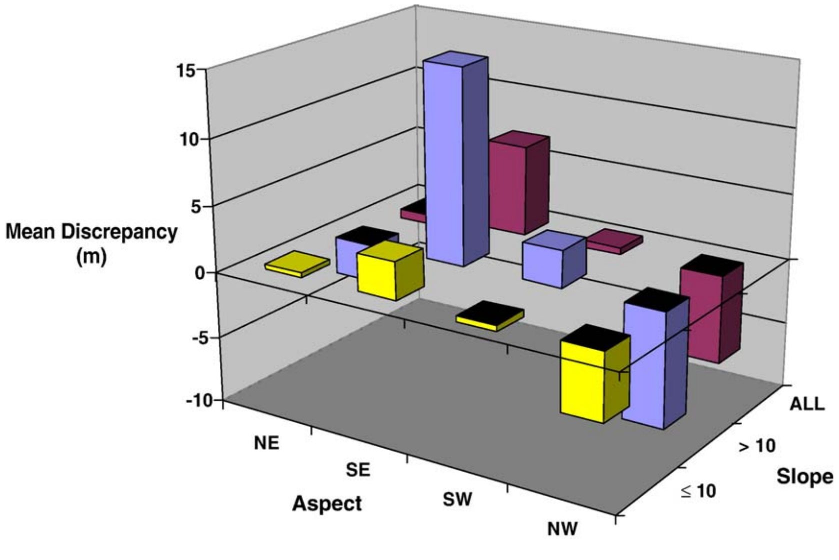

Fig. 6. Discrepancy between SRTM and GPS data as a function of slope and aspect characteristics of the terrain; Phuket study area.

standard error of the estimate by 40% for Phuket (from 10.85 m to 6.50 m) and 12% for Catskills data (from 4.73 m to 4.15 m).

Aspect of the terrain was found to have influence on both the magnitude and the sign of errors in the CGIAR-CSI SRTM data. Because of the uneven distribution of the Catskill Mountains area sites according to aspect characteristic, we decided to exclude Catskills data from the analysis of aspect impact on CGIAR-CSI SRTM accuracy and use only data obtained from the Phuket study area. The highest magnitude of errors was observed for measurements made on slopes facing northwest (NW) and southeast (SE). Correspondingly, CGIAR-CSI SRTM measurements underestimated elevations of slopes facing NW and overestimated elevations of slopes facing SE (Fig. 6). This tendency was present irrespectively of the slope value; however, measurements made on terrains with slope values higher than 10° resulted in greater errors and only in this group aspect impact on errors was statistically significant (Table 5).

4.3. Ways to improve CGIAR-CSI SRTM data accuracy

Accuracy improvement was ascertained by comparing standard errors of the estimate (S.E.E.) resulting from multiple regression analysis (with CGIAR-CSI SRTM, aspect, and slope as independent variables) and linear regression analysis (with CGIAR-CSI SRTM as a single independent variable). GPS data represented dependent variable in both analyses. Analyses were applied to Catskills data (data range "slope ≤ 10°"), to Phuket data (data ranges "slope ≤ 10°", "slope > 10°", and "all"), and to a combined set of data consisting of Catskills and Phuket measurements pooled together (data ranges "slope ≤ 10°", "slope > 10°", and "all").

In all cases, application of multiple regression resulted in smaller S.E.E. For the whole range of slope values and for slopes less than 10°, the improvement was negligible (0.1 to 0.7 m). However, application of multiple regression to data range "slope > 10°" decreased SEE by 3.93 m (Phuket dataset) and 3.95 m (combined dataset) (Fig. 7).

Derived multiple regression equation ($\text{GPS} = P_0 + P_1{*}\text{Aspect} + P_2{*}\text{Slope} + P_3{*}\text{SRTM}$) for combined dataset had fitted parameters and r^2 value as follows: $P_0 = 32.061$, $P_1 = 0.046$, $P_2 = -2.827$, $P_3 = 0.970$, $r^2 = 0.9906$. ANOVA test, performed on the regression data, showed the correlation to be highly significant ($p < 0.0001$), thus, confirming statistical validity of the proposed multiple regression model as a way of relating the slope and aspect characteristics of the terrain to the accuracy of CGIAR-CSI SRTM data.This model in its present form is valid for the currently available dataset, but, naturally, will be updated as new data become available.

Table 5
Analysis of discrepancies between SRTM and GPS data as a function of slope and aspect characteristics of the terrain; Phuket study area

Slope	Aspect			
	NE	SE	SW	NW
≤10°	0.39 ± 1.81	2.83 ± 1.70	−0.51 ± 1.75	−5.14 ± 2.13
>10°	−2.84 ± 1.87	14.90 ± 2.49	2.80 ± 2.08	−8.82 ± 2.05
All	−0.78 ± 1.40	6.93 ± 1.59	0.52 ± 1.46	−6.79 ± 2.14

Data = mean ± S.E.M. Statistical significance was achieved in "all" (SE vs. NW, $p = 0.011$) and in ">10°" slope categories (NE vs. SE, $p = 0.0018$; NE vs. NW, $p = 0.044$; SE vs. SW, $p = 0.034$; SE vs. NW, $p = 0.006$; SW vs. NW, $p = 0.026$); test: one-way ANOVA followed, when applicable, by multiple comparison tests with Bonferroni correction.

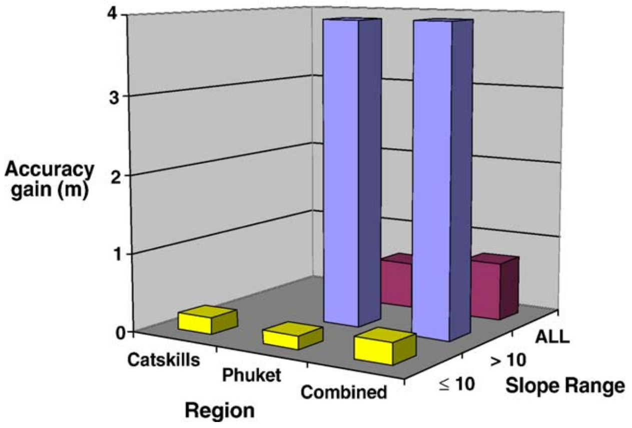

Fig. 7. Accuracy gain achieved through application of multiple regression analysis with aspect, slope, and SRTM data as independent variables.

5. Conclusions

Analyses presented in this paper indicate that:

1. Absolute vertical accuracy of CGIAR-CSI SRTM data for our datasets proved to be two to four times higher than the value of 16 m presented in the original SRTM requirement specification.
2. Both slope and aspect characteristics of the terrain have significant impact on accuracy of CGIAR-CSI SRTM data. Accuracy particularly suffers on terrains with slope values higher than 10°. Aspect of the terrain influences both the magnitude and the sign of errors in the CGIAR-CSI SRTM data. CGIAR-CSI SRTM data underestimate elevations of slopes facing NW and overestimate elevations of slopes facing SE, but the errors are significant only on terrains with slope values exceeding 10°. Quality of collected SRTM data also depends on incidence angles that affect differential distances for ground targets and the accuracy of original data (Jarvis et al., 2004). These angles could be potentially taken into account in studies that use original SRTM data.
3. When slope and aspect information is available, use of such information by means of incorporating it into a multiple regression model will considerably improve accuracy of CGIAR-CSI SRTM data, but apparently, meaningful gain in accuracy will only be achieved on terrains with slope values exceeding 10°. On less rugged terrain accuracy, improvement is negligible and use of multiple regression analysis in those cases seems impractical.
4. Developed regression curves can be used as a basis for a comprehensive database that will be updated as new data become available. The most efficient implementation of this approach can be achieved using Internet-based technologies. For the spatial reference and location of geographic areas

described by the regression models, Internet map servers such as Google Earth can provide an invaluable platform (Ullman & Gorokhovich, 2006). Its simplicity as well as availability of application program interface (API) will allow development of tools to enhance use of SRTM data in many environmental applications.

5. Role of vegetation was not fully assessed in this study. It is assumed that in both geographic areas vegetation covers uniformly (height and density) 90 × 90 m square (pixel size of CGIAR-CSI SRTM product). In this case, the associated error would be constant and, therefore, would not affect described relationships.
6. The results of accuracy assessment also depend on the number of GPS readings per one spatial unit of CGIAR-CSI SRTM data (i.e., 90 m). The more GPS readings would be available, the more accurate the final estimation will be. However, implementation of this approach requires special planning of GPS surveys and considerable additional resources, and was not within the scope of the present study.

Acknowledgements

Many thanks to Ms. Patricia Ahmetaj and Ms. Lori Machung, New York City Department of Environmental Protection, for their assistance in field data collection in Catskill Mountains. Mr. Woody from Phuket (Thailand) provided invaluable assistance in field work during May 2005.

References

Blomenhofer, H., Hein, G., Blomenhofer, E., & Werner, W. (1994). *Development of a Real-Time DGPS System in the Centimeter Range, IEEE 1994, Position, Location, and Navigation Symposium, Las Vegas NV* (pp. 532–539).

Blumberg, D., Bach, D., Weissel, J., Gorokhovich, Y., Small, C., & Balk, D. (2005). The 2004 Sumatra tsunami event: Contribution of SRTM data to the analysis of devastation. *The Shuttle Radar Topography Mission—Data Validation and Applications, Workshop, June 14–16, 2005, Reston, Virginia*.

Burrough, P. A. (1986). *Principles of geographical information systems for land resources assessment* (pp. 50). New York: Oxford University Press.

Dowding, S., Kuuskivi, T., & Li, X. (2004). Void fill of SRTM elevation data—principles, processes and performance. *Proceedings of the conference "ASPRS Images to Decision: Remote Sensing Foundation for GIS Applications", Kansas City, MO, September 12–16*.

ESRI (2005) Environmental Systems Research Institute, Inc., Help Topics, ArcInfo Help, version 9.1. ArcDoc, version 9.1.

Falorni, G., Teles, V., Vivoni, E. R., Bras, R. L., & Amaratunga, K. (2005). Analysis and characterization of the vertical accuracy of digital elevation models from the shuttle radar topography mission. *Journal of Geophysical Research*, *110*, F02005.

Farr, T. G., & Kobrick, M. (2000). Shuttle radar topography mission produces a wealth of data. *Transactions of the American Geophysical Union*, *81*, 583−585.

Farrell, J., Givargis, T., & Barth, M. (1999). Differential carrier phase GPS-aided INS for automotive applications. *Proceedings of the American Control Conference, San Diego, CA, June 1999*.

Farrell, J. A., Tan, H. -S., & Yang, Y. (2003). Carrier phase GPS-aided INS-based vehicle lateral control. *Journal of Dynamic Systems, Measurement, and Control*, *125*(3), 339−353.

Gamba, P., Dell'Acqua, F., & Houshmand, B. (2002). SRTM data characterization in urban areas. International Society for Photogrammetry and Remote Sensing Commission III, Symposium 2002, September 9– 13, 2002, Graz, Austria 2004–2008.

Guth, P. (2003). Geomorphology of DEMs: Quality assessment and scale effects. Paper No. 175-2. *Proceedings of GSA, Seattle Annual Meeting, November 2–5, 2003*.

Helm, A., Braun, A., Eickschen, S., & Schune, T. (2002). Calibration of the shuttle radar topography mission X-SAR instrument using a synthetic altimetry data model. *Canadian Journal of Remote Sensing*, *28*(4), 573−580.

Jarvis, A., Rubiano, J., Nelson, A., Farrow, A., & Mulligan, M. (2004). Practical use of SRTM data in the tropics—comparisons with digital elevation models generated from cartographic data. *Working Document*, *Vol. 198*. Centro Internacional de Agricultura Tropical (CIAT) 32 pp.

Jennings, M. E., Thomas, W. O., Jr., & Riggs, H. C. (1994). Nationwide summary of U.S. Geological Survey regional regression equations for estimating magnitude and frequency of floods for ungaged sites, 1993. *U.S. Geological Survey Water-Resources Investigations Report 94-4002* (196 pp. Superseded by WRIR 01-4168).

Kellndorfer, J., Walker, W., Pierce, L., Dobson, C., Fites, J. A., Hunsaker, C., et al. (2004). Vegetation height estimation from shuttle radar topography mission and national elevation datasets. *Remote Sensing of Environment*, *93*, 339−358.

Koch, A., & Lohmann, P. (2000). Quality assessment and validation of digital surface models derived from the shuttle radar topography mission (SRTM). *Proceedings, IAPRS, Vol. XXXIII, Amsterdam, 2000*.

Miliaresis, G. Ch., & Paraschou, C. V. E. (2005). Vertical accuracy of the SRTM DTED level 1 of crete. *International Journal of Applied Earth Observation and Geoinformation*, *7*(1), 49−59.

Muller, J. P. (2005). Quantitative assessment of C-band and X-band SRTM datasets over the CEOS-WGCV-TMSG test sites and intercomparison of C-band DEM with the OS® PANORAMA DTM. *The Shuttle Radar Topography Mission—Data Validation and Applications, Workshop, June 14–16, 2005, Reston, Virginia*.

Rabus, B., Eineder, M., Roth, A., & Bamler, R. (2003). The shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar. *Journal of Photogrammetry and Remote Sensing*, *57*, 241−262.

Rodriguez, E., Morris, C. S., Belz, J. E., Chapin, E. C., Martin, J. M., Daffer, W., et al. (2005). *An assessment of the SRTM topographic products, Technical Report JPL D-31639.*Pasadena, California: Jet Propulsion Laboratory 143 pp.

Shelton, R. K., Ma, L. -S., Kapteyn, H. C., Murnane, M. M., Hall, J. L., & Ye, J. (2002). Active synchronization and carrier phase locking of two separate mode-locked femtosecond lasers. *Journal of Modern Optics*, *49*(3/4), 401−409.

Smith, B., & Sandwell, D. (2003). Accuracy and resolution of shuttle radar topography mission data. *Geophysical Research Letters*, *30*(9), 1467.

Stock, J. D., Bellugi, D., Dietrich, W. E., & Allen, D. (2002). Comparison of SRTM topography to USGS and high resolution laser altimetry topography in steep landscapes: Case studies from Oregon and California. *Eos Trans. AGU, Fall Meet. Suppl., Abstract H21G-09, 2002*, *Vol. 83(47)*.

Sun, G., Ranson, K. J., Kharuk, V. I., & Kovacs, K. (2003). Validation of surface height from shuttle radar topography mission using shuttle laser altimeter. *Remote Sensing of Environment*, *88*, 401−411.

Trimble Navigation Ltd. (2004). Datasheet. See: http://trl.trimble.com/docushare/dsweb/Get/Document-128930/13273F_GPSPathProXR_DS_1004_lr.pdf, (last time accessed June, 2005).

Ullman, L., & Gorokhovich, Y. (2006). Google Earth and some practical applications for the field of archaeology.*CSA Newsletter*, *XVIII*(3) (http://www.csanet.org/newsletter/winter06/nlw0604.html)

Werner, M. (2001). Shuttle radar topography mission (SRTM), mission overview. *Journal of Telecommunication (Frequenz)*, *55*, 75−79.