Accuracy Assessment of the U.S. Geological Survey National Elevation Dataset, and Comparison with Other Large-Area Elevation Datasets—SRTM and ASTER

Open-File Report 2014–1008

U.S. Department of the Interior
U.S. Geological Survey

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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2014

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Suggested citation:
Gesch, D.B., Oimoen, M.J., and Evans, G.A., 2014, Accuracy assessment of the U.S. Geological Survey National Elevation Dataset, and comparison with other large-area elevation datasets—SRTM and ASTER: U.S. Geological Survey Open-File Report 2014–1008, 10 p., *http://dx.doi.org/10.3133/ofr20141008*.

ISSN 2331-1258 (online)

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to the distance above the vertical datum.

Accuracy Assessment of the U.S. Geological Survey National Elevation Dataset, and Comparison with Other Large-Area Elevation Datasets—SRTM and ASTER

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Introduction

The National Elevation Dataset (NED) is the primary elevation data product produced and distributed by the U.S. Geological Survey (USGS). The NED provides seamless raster elevation data of the conterminous United States (CONUS), Alaska, Hawaii, U.S. island territories, Mexico, and Canada. The NED is derived from diverse source datasets that are processed to a specification with consistent resolutions, coordinate system, elevation units, and horizontal and vertical datums (Gesch and others, 2002). The NED serves as the elevation layer (Gesch and others, 2009) of *The National Map* (Kelmelis and others, 2003), and it provides basic elevation information for earth science studies and mapping applications in the United States and most of North America. Details on the background, history, specifications, production, and applications of the NED are available in Gesch and others (2002), Gesch (2007), and Gesch and others (in press). The focus of this report is on the vertical accuracy of the NED and on comparison of the NED with other similar large-area elevation datasets, namely data from the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER).

Accuracy and Data Quality

Users of the NED are interested in the accuracy of its elevation values (herein after 'accuracy'), as that characteristic is a primary factor in how suitable the data are for a specific application and in the quality of derivative products. For example, the vertical accuracy of the NED directly controls the water-level increment that can be effectively modeled in sea-level rise vulnerability assessments (Gilmer and Ferdaña, 2012; Gesch, 2013; Thatcher and others, 2013). The accuracy of the NED varies spatially because of the variable quality of the source data. As such, the NED inherits the accuracy of the source digital elevation models (DEMs). In an effort to provide detailed information to users on the vertical accuracy of the NED, the April 2013 release version of the dataset was tested by comparing it with an independent reference source of very high accuracy. The reference data are the geodetic control points that the National Geodetic Survey (NGS) uses for development of its hybrid geoid models (Smith and Roman, 2001; Roman and others, 2004; Roman and others, 2010), in this case their latest model GEOID12A. These points represent NGS's best x-y-z control point dataset. The points have millimeter- to centimeter-level accuracies, so they are an excellent reference against which to assess the accuracy of the NED. The distribution of this dataset of more than 25,000 survey points, referred to by NGS as "GPS on bench marks" (National Geodetic Survey, 2012), across North America is shown in figure 1.

Absolute Vertical Accuracy

To complete the accuracy assessment, the NED elevation value at each NGS control point location was derived through bilinear interpolation at the precise latitude/longitude location of the point, and error statistics were calculated. At each point, the difference was calculated by subtracting the GPS bench mark elevation from the NED elevation, and these differences are the measured errors in the NED. This approach produces error statistics that are easy to interpret, with positive errors representing locations where the NED elevations are too high and negative errors occurring at locations where the NED elevations are too low compared to the reference control points.

The assessment was done by area and NED resolution for CONUS (1/3-arc-second data) (table 1), Alaska (2-arc-second data), and Canada and Mexico (1-arc-second data) (table 2). The overall absolute vertical accuracy for each area is expressed as the root mean square error (RMSE), a widely used error metric for documenting elevation data accuracy (Maune and others, 2007). Accuracy expressed in terms of the National Map Accuracy Standards (NMAS), which use a 90 percent confidence level, and in terms of the National Standard for Spatial Data Accuracy (NSSDA), which uses a 95 percent confidence level also are shown in table 1. The methods described in Maune and others (2007) were used to

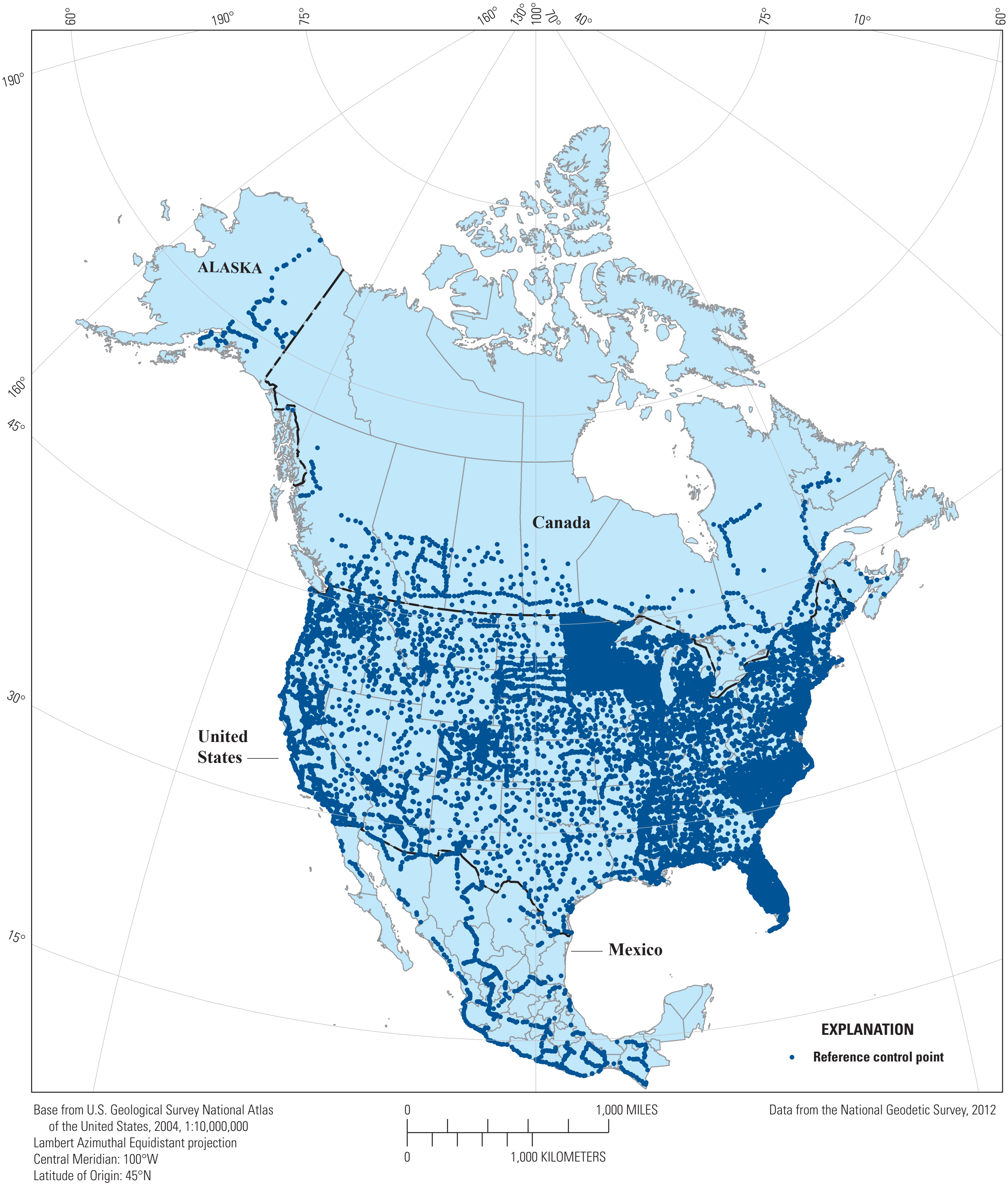

Figure 1. The reference control point dataset used for accuracy assessment of the National Elevation Dataset consists of the "GPS on bench marks" associated with the National Geodetic Survey's GEOID12A model.

Table 1. National Elevation Dataset (NED) absolute vertical accuracy for the conterminous United States as measured against reference geodetic control points.

[Error statistics are in meters. Accuracy assessment for the April 2013 1/3-arc-second version of the NED was done with bench marks associated with GEOID12A from the National Geodetic Survey (NGS). For comparison purposes, also reported are the numbers from an assessment of the June 2003 version of the 1-arc-second NED (Gesch, 2007) using bench marks associated with GEOID03 from NGS. RMSE, root mean square error; NMAS, National Map Accuracy Standards; %, percent; NSSDA, National Standard for Spatial Data Accuracy; NDEP, National Digital Elevation Program]

NED version	Number of reference points	Minimum	Maximum	Mean	Standard deviation	RMSE	NMAS (90%)	NSSDA (95%)	NDEP (95th percentile)
April 2013	25,310	-24.64	15.57	-0.29	1.52	1.55	2.55	3.04	3.02
June 2003	13,305	-42.64	18.74	-0.32	2.42	2.44	3.99	4.75	5.59

Table 2. National Elevation Dataset (NED) absolute vertical accuracy as measured against reference geodetic control points.

[Error statistics are in meters. Accuracy assessment for the April 2013 version of the NED was done with bench marks associated with GEOID12A from the National Geodetic Survey. RMSE, root mean square error]

NED area and resolution	Number of reference points	Minimum	Maximum	Mean	Standard deviation	RMSE
Alaska 2-arc-second	106	-19.64	16.17	-1.44	4.66	4.85
Canada 1-arc-second	578	-18.94	12.29	-0.63	3.53	3.64
Mexico 1-arc-second	675	-20.68	36.66	0.98	6.68	6.74

convert the measured vertical RMSE to equivalent NMAS and NSSDA expressions. Although the RMSE is a widely used error metric, it has been noted that in many cases elevation errors do not follow a normal distribution, so a key assumption in the NSSDA approach to computing the 95 percent confidence level based on the RMSE may be violated (Liu and others, 2012). To address this condition, the National Digital Elevation Program (NDEP) has recommended use of the 95th percentile method of expressing accuracy (National Digital Elevation Program, 2004; Maune and others, 2007). For completeness, table 1 also includes the CONUS NED accuracy expressed as the NDEP 95th percentile error, which is interpreted as stating that 95 percent of the errors have absolute values less than or equal to the reported value.

For CONUS, there appears to be no correlation of NED error and GPS bench mark elevation value (fig. 2), and there is no preference for negative or positive errors. The scatter plot in figure 2 shows the data points uniformly distributed about the zero error axis, so users can expect a consistent range of errors regardless of elevation magnitude for a given area.

The RMSE of 1.55 meters for the NED covering CONUS is a marked improvement from the previously published accuracy value of 2.44 meters for an earlier version of the NED (Gesch, 2007). The time interval between the two versions of the NED is nearly 10 years, and the source data for much of CONUS has changed substantially, which has resulted in the observed improvement in overall accuracy (table 1). More than 60 percent of the NED covering CONUS was updated between the June 2003 and April 2013 releases of the NED. About two-thirds of the updated area is due to 10-meter 7.5-minute quadrangle-based DEMs derived from 1:24,000-scale hypsography (contours and spot heights) replacing older 30-meter versions of the source DEMs. The remaining one-third of the updated area is where lidar or other high-resolution source DEMs replaced 30-meter or 10-meter quadrangle-based DEMs. Examination of the NED error statistics in just the updated area indicates the effects of integrating improved source data between the June 2003 and April 2013 versions of the NED. In June 2003 the area exhibited an RMSE of 2.43 meters, and in April 2013 the same area had an accuracy of 1.29 meters RMSE. Looking in more detail at the new source data types for the updated area exhibits an RMSE of 1.62 meters for the two-thirds of the area where 10-meter DEMs replaced 30-meter DEMs, and an RMSE of 0.87 meter for the one-third of the area where lidar and digital photogrammetry source data replaced USGS quadrangle-based DEMs (10- or 30-meter).

Use of the NED spatially referenced metadata (Gesch, 2007; Gesch and others, in press) allows for calculation of accuracy statistics segmented by source DEM characteristics. Because the NED is derived from source DEMs that were produced with several different methods (Gesch and others, in press), it may be important for a user to know what levels of accuracy can be expected for areas based on DEMs produced with the various methods. Error statistics for the areas of the NED derived from each of the four primary production methods are shown in table 3. The advantages of newer, high-resolution source data are recognized in the better accuracy compared to the accuracy of the 1:24,000-scale quadrangle-based data. The RMSE for the second source (lidar; 0.87 meter), the

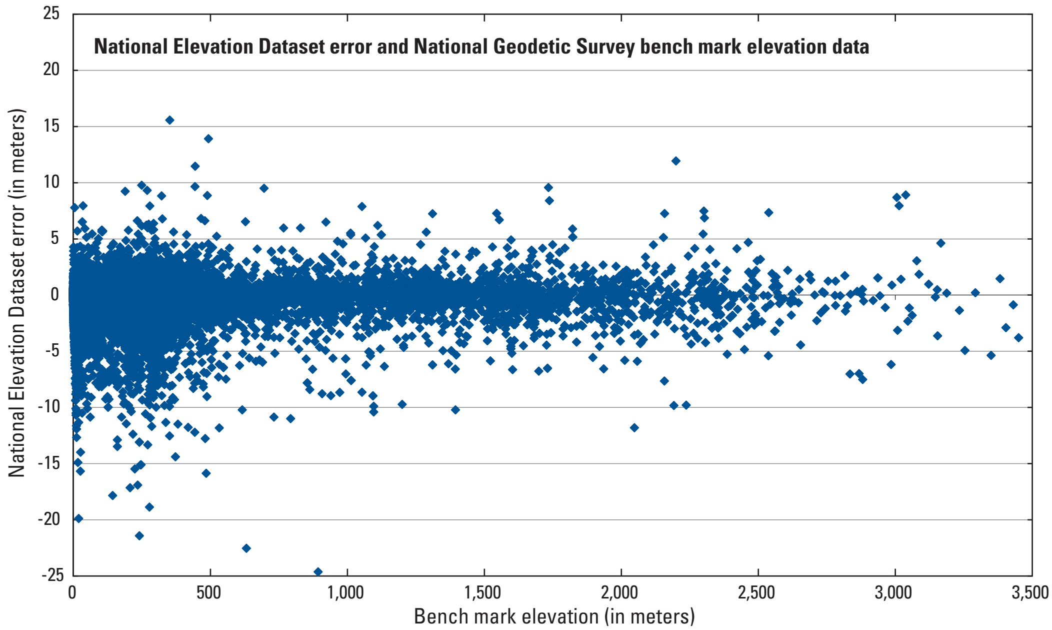

Figure 2. National Elevation Dataset (NED) errors (in meters) plotted against National Geodetic Survey (NGS) bench mark elevation data.

Table 3. National Elevation Dataset (NED) absolute vertical accuracy for the conterminous United States as measured against reference geodetic control points.

[The results have been segmented by the four primary types of source data production method. Error statistics are in meters. Accuracy assessment for the April 2013 1/3-arc-second version of the NED was done with bench marks associated with GEOID12A from the National Geodetic Survey. RMSE, root mean square error]

Source data production method	Number of reference points	Minimum	Maximum	Mean	Standard deviation	RMSE
LT4X (1:24,000 hypsography)	14,813	-24.64	15.57	-0.36	1.85	1.89
Lidar	10,281	-22.53	4.66	-0.19	0.85	0.87
Photogrammetric mass points and breaklines	146	-6.81	1.69	-0.28	1.12	1.15
Airborne digital stereo image correlation	70	-2.15	1.13	0.18	0.45	0.48

third source (mass points and breaklines; 1.15 meters), and the fourth source (image correlation; 0.48 meter) in table 3 is smaller than that for the first source (1:24,000-scale hypsography; 1.89 meters).

For the areas in the NED derived from USGS 7.5-minute quadrangle-based DEMs (produced from 1:24,000-scale maps), the 1.89-meter RMSE (table 3) as an accuracy statement is an actual measured quantity, so is more advantageous than the often quoted RMSE of 7 meters for USGS DEMs. The 7-meter RMSE, often cited as the vertical accuracy of USGS 7.5-minute DEMs, is simply a production goal described in the USGS Data Users Guide 5—Digital Elevation Models, last published in 1993 and traditionally known by many DEM users as the "blue book" (see also U.S. Geological Survey, 1997). The 7-meter RMSE is not, nor has it ever been, a measured accuracy assessment of the NED.

The vertical accuracy of the NED also varies by land cover. The National Land Cover Database (NLCD) (Fry and others, 2011) provides land cover information for each reference control point location. The accuracy of the NED for different land cover types as compared to the overall NED absolute vertical accuracy of 1.55 meters RMSE is shown in table 4.

For Alaska, segmenting the accuracy assessment results by source data type (based on the spatially referenced metadata) shows the advantages of integrating new, improved source DEMs into the NED. The source data for most of Alaska are DEMs derived from 1:63,360-scale topographic maps, but there is an ongoing program to collect improved elevation data for the State, in this case 5-meter spatial resolution DEMs derived from airborne interferometric synthetic aperture radar (IFSAR) data. Where available, these new data have been integrated into the NED, resulting in a substantial improvement from the older cartographic source data, which have been shown to be lacking in the required accuracy and quality for many applications (Maune, 2008). The overall accuracy for Alaska is 4.85 meters RMSE (table 2), but for the areas derived from the IFSAR source DEMs the

Table 4. National Elevation Dataset (NED) absolute vertical accuracy for the conterminous United States as measured against reference geodetic control points.

[The results have been segmented by land cover classes from the National Land Cover Database (NLCD) 2006. Error statistics are in meters. Accuracy assessment for the April 2013 1/3-arc-second version of the NED was done with bench marks associated with GEOID12A from the National Geodetic Survey. RMSE, root mean square error]

Land cover class	Number of reference points	Minimum	Maximum	Mean	Standard deviation	RMSE
Developed, Open Space	8,247	-24.64	15.57	-0.15	1.31	1.32
Developed, Low Intensity	6,680	-14.91	13.92	-0.27	1.48	1.50
Developed, Medium Intensity	3,081	-15.12	7.88	-0.54	1.80	1.88
Developed, High Intensity	695	-21.43	6.62	-0.79	2.32	2.45
Barren Land	246	-19.88	7.79	-0.86	2.42	2.57
Deciduous Forest	356	-11.80	3.57	-0.33	1.48	1.52
Evergreen Forest	197	-13.09	5.17	-0.62	2.22	2.30
Mixed Forest	83	-9.82	3.66	-0.88	2.20	2.36
Shrub/Scrub	878	-17.84	8.87	-0.51	2.17	2.22
Grassland/Herbaceous	856	-11.82	7.34	-0.33	1.55	1.58
Pasture/Hay	1,295	-8.82	5.77	-0.18	1.18	1.19
Cultivated Crops	1,889	-11.48	5.77	-0.14	1.01	1.02
Woody Wetlands	414	-15.68	8.91	-0.42	1.59	1.64
Emergent Herbaceous Wetlands	393	-10.10	3.17	-0.51	1.50	1.59
All	25,310	-24.64	15.57	-0.29	1.52	1.55

RMSE is 1.63 meters, which is much better than the RMSE of 6.32 meters for areas derived from the cartographic source DEMs.

Relative Vertical Accuracy

For some applications of elevation data, the relative, or point-to-point, vertical accuracy is more important than the absolute vertical accuracy. Whereas absolute accuracy accounts for the combined effects of systematic and random errors, relative accuracy is a measure of just random errors. The relative vertical accuracy of a dataset is especially important for derivative products that use the local differences among adjacent elevation values, such as slope and aspect calculations (National Digital Elevation Program, 2004). To characterize the relative vertical accuracy of the NED, the same set of reference geodetic control points used in the assessment of absolute vertical accuracy was processed and analyzed. For CONUS, each point in the reference control point dataset was processed to identify its closest neighboring point, and this resulted in 15,509 unique point pairs for which the NED elevation at each point location and the distance between the points were recorded. The relative vertical accuracy, *RV*, was calculated for each point pair using the following formula (National Digital Elevation Program, 2004):

$$RV = |\Delta\text{ref} - \Delta\text{NED}| \quad (1)$$

where

$$\Delta\text{ref} = |\text{reference elevation difference}| \quad (2)$$

$$\Delta\text{NED} = |\text{NED elevation difference}| \quad (3)$$

Because assessing relative accuracy across very long distances can have the effect of averaging random errors (thereby reducing the overall error), a subset of the point pairs with closely spaced points was used to characterize the relative vertical accuracy of the NED (table 5). Averaged from the 1,068 point pairs (with distances of less than 500 meters), the relative vertical accuracy is 0.81 meter. Expressed as the 95th percentile, the relative vertical accuracy is 2.93 meters, meaning that 95 percent of the point pairs exhibit a relative difference of 2.93 meters or less. The slope accuracy (expressed as the mean and 95th percentile) as derived from the relative vertical accuracy fit within a 3-by-3 window of raster elevation cells (Gesch, 2007) is shown in table 5. As noted previously in the Absolute Vertical Accuracy section, integration of high-resolution source data into the NED between June 2003 and April 2013 has improved NED quality, in this case better relative vertical accuracy and the corresponding slope accuracy.

Table 5. National Elevation Dataset (NED) relative (point-to-point) vertical accuracy for the conterminous United States measured using closely spaced (less than 500 meters) National Geodetic Survey control points as the reference information.

[Assessment of the April 2013 version of the 1/3-arc-second NED was done with bench marks associated with GEOID12A, and assessment of the June 2003 version of the 1-arc-second NED was done using bench marks associated with GEOID03. Slope accuracy was calculated based on the relative vertical accuracy as described in Gesch (2007). °, degree; %, percent]

NED version	Number of unique point pairs	Minimum (meters)	Maximum (meters)	Mean (meters)	Standard deviation (meters)	95th percentile (meters)	1-arc-second slope accuracy (mean)	1-arc-second slope accuracy (95th percentile)
April 2013	1,068	0	10.71	0.81	1.19	2.93	0.77° (1.35% slope)	2.79° (4.88% slope)
June 2003	700	0	21.53	1.30	1.79	4.87	1.24° (2.17% slope)	4.64° (8.12% slope)

Accuracy Assessment Caveats

One caveat to note about the accuracy assessment presented here is that even though the reference control point dataset is large, the number of source DEMs on which the points are located is relatively small compared to the total number of source DEMs. For CONUS, approximately 12 percent of the source DEMs have at least one point located within the DEM; thus, if users need specific accuracy information for the NED for a local area, a separate assessment should be done with suitable reference data just for that area. In addition, even though the reference control points are located broadly across CONUS, the distribution of elevations and terrain conditions within the dataset is not completely representative of the Nation's topography. This stands to reason, as surveyed bench marks are generally located in open, accessible areas; thus, high elevation, steep slope locations are under-represented in the reference dataset.

Also, for CONUS about 40 percent of the reference points are located on 20 percent of the area covered by high-resolution source data, and 80 percent of the area covered by cartographic-based source data contains about 60 percent of the reference points, so proportions of source data and reference points do not match. Such a mismatch in proportions may affect the overall vertical accuracy number because more data points are located in areas of higher accuracy source DEMs. To check this limitation, a stratified random sample of reference points was collected for each source data type (table 3) to match the proportion of CONUS area derived from each type. These samples were then combined to calculate an overall absolute vertical accuracy. The results indicate a slightly worse overall accuracy, 1.77 meters RMSE as compared to 1.55 meters RMSE, when compared to the number calculated from the full reference point set that has a disproportionate distribution among source data types. If NED is being used over a limited size area, users may find it beneficial to focus more on the NED vertical accuracy associated with the predominant source data type (table 3) in that area rather than the overall accuracy number calculated from points across all of CONUS.

Despite these limitations with the reference data, the overall vertical accuracy reported here is useful for applications that need to factor in the quality of the NED over large areas. As the NED is continually upgraded based on new acquisitions of high-resolution data, the overall vertical accuracy will improve. In many cases, the source datasets will have comprehensive error reports supplied with them, and these statistics will be captured, preserved, and linked to the NED metadata.

Comparison with Other Large-Area Elevation Datasets

A common question from users of the NED is how it compares with other similar seamless elevation datasets that cover broad areas. In particular, two other datasets of interest are SRTM data (Farr and others, 2007) and the ASTER Global Digital Elevation Model (GDEM) (Abrams and others, 2010). The SRTM data and ASTER GDEM are 1-arc-second datasets that have near global coverage and represent substantial advances in freely available high resolution global elevation data (Gesch, 2012). The SRTM data became available within a few years after the space shuttle mission flew in 2000. The ASTER GDEM was first released in 2009, and an improved version was released in 2011. After the second version was produced, SRTM and ASTER GDEM were assessed against NGS GPS bench mark control points, in this case the points associated with the GEOID09 model. For comparison purposes, the 1-arc-second layer of the NED also was assessed with the same reference control points. Before comparison against the reference points, SRTM and ASTER GDEM were adjusted to be in the same vertical datum (North American Vertical Datum of 1988) of the NGS bench marks, as the native vertical datum for SRTM and ASTER GDEM is the Earth Gravitational Model 1996 geoid. The accuracy assessment results (Gesch and others, 2012) show SRTM and ASTER GDEM to be less accurate than the NED, with SRTM exhibiting an RMSE of 4.01 meters and ASTER GDEM exhibiting an RMSE of 8.68 meters, compared to an RMSE of 1.84 meters for the NED. The SRTM data and ASTER GDEM also both show a positive elevation bias in built-up and forested areas, as they both are derived from systems that collect what is termed “first surface” data that do not measure ground elevations in the presence of buildings and vegetation canopies. The NED does not exhibit a positive vertical bias in these areas because by definition it is a bare-earth elevation model.

Further analysis comparing SRTM data with the NED indicates distinctions that may be important for users to consider, especially for derivative products. Slope and aspect comparisons at the locations of reference control points reveal that values derived from the 1-arc-second NED layer and SRTM data can differ substantially. In this case, the reference data were the NGS GPS bench marks associated with GEOID03, numbering more than 13,000 points in CONUS. The NED used in the analysis was an earlier version (June 2003) constructed only from USGS 7.5-minute quadrangle-based DEMs. Corresponding NED and SRTM slope values at the reference control point locations indicate substantial variability (fig. 3). The SRTM data indicate overall higher slopes compared to the NED, especially in lower slope categories (1–5 degrees) (fig. 4), which is likely due, in part, to the space-borne IFSAR source data for SRTM that tend to have higher noise content (local variability) than other systems that collect elevation data. The slope analysis further reveals that both

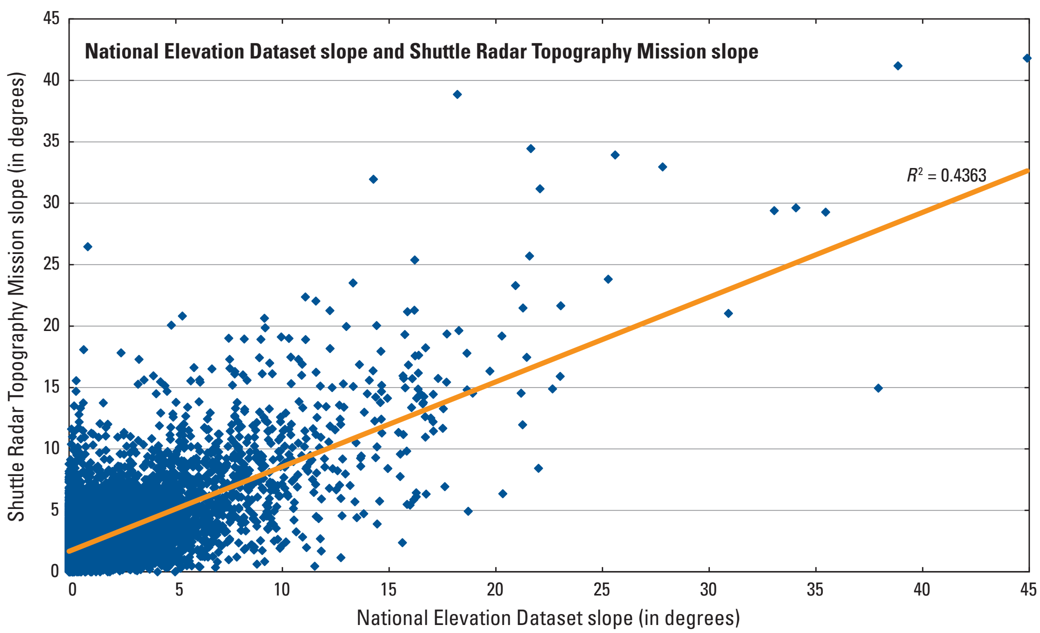

Figure 3. Comparison between corresponding National Elevation Dataset (NED) and Shuttle Radar Topography Mission (SRTM) slope values at reference control point locations.

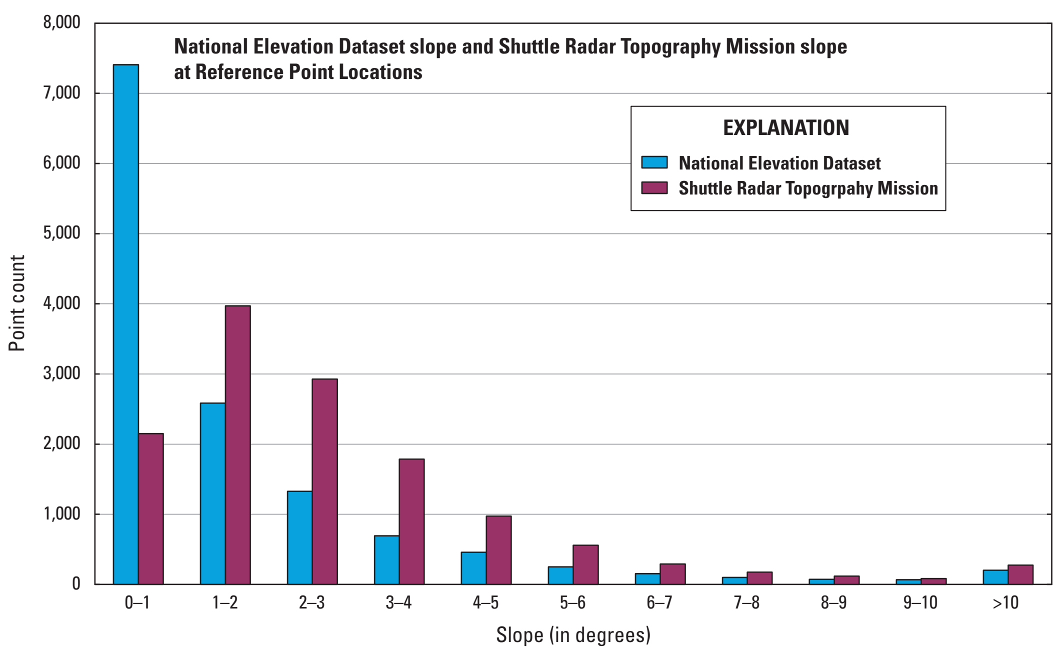

Figure 4. A comparison of corresponding National Elevation Dataset (NED) and Shuttle Radar Topography Mission (SRTM) slope values shows that SRTM exhibits overall higher slopes compared to the NED, especially in lower slope categories.

the NED and SRTM errors are strongly correlated with slope (fig. 5), although the NED exhibits lower overall error than SRTM across the range of slope categories. Corresponding aspect values derived from the NED and SRTM also can vary substantially between the two datasets (fig. 6). In this comparison, aspect values have been categorized into 45-degree bins centered on the cardinal and diagonal compass directions. More than 40 percent of the corresponding aspect values differ by 90 degrees or more between the NED and SRTM.

Based on the analyses from this report, users should not expect consistent data characteristics and error patterns between the NED and SRTM, so each dataset would not be a direct replacement or substitute for the other. However, the datasets can be viewed as being complementary, and some applications have exploited this unique pairing of seamless, large-area coverage elevation datasets to derive information products. Several investigators have taken advantage of the bare-earth nature of the NED and the first return nature of the SRTM to calculate vegetation canopy heights (Kellndorfer and others, 2004; Walker and others, 2007; Yu and others, 2010; Ni and others, 2013). The temporal differences between the acquisition dates for the NED and SRTM source data have been exploited to map areas of significant topographic changes in CONUS because of surface mining, road construction, urban development, landfills, and dam construction and reservoir filling (Gesch, 2005; Gesch, 2006; see also: *http://topochange.cr.usgs.gov/*).

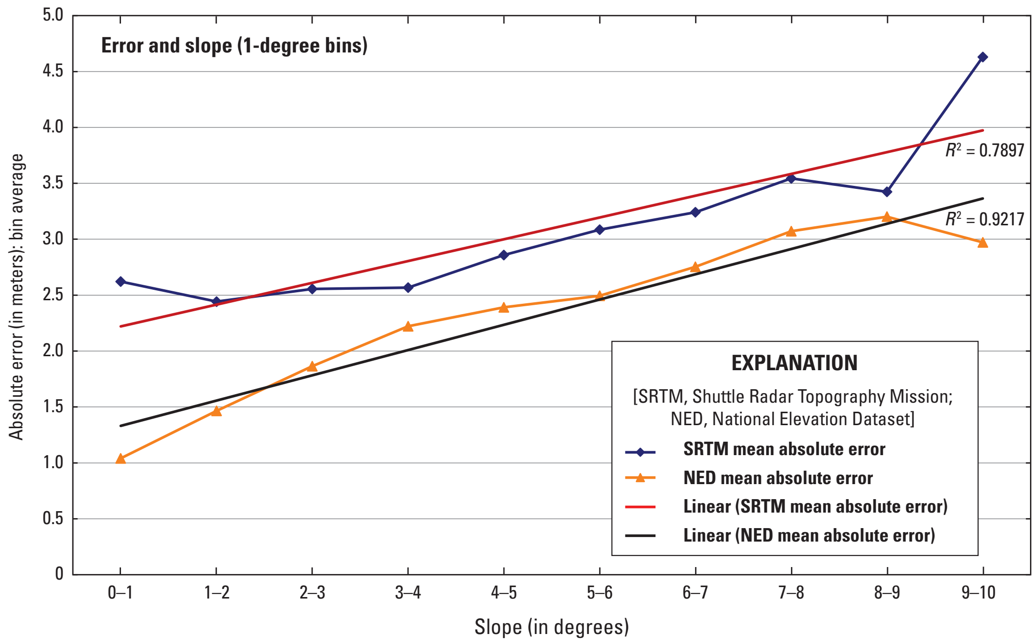

Figure 5. National Elevation Dataset (NED) and Shuttle Radar Topography Mission (SRTM) errors are strongly correlated with slope (increasing error with increasing slope), although the NED exhibits lower overall error than SRTM across the range of slope categories.

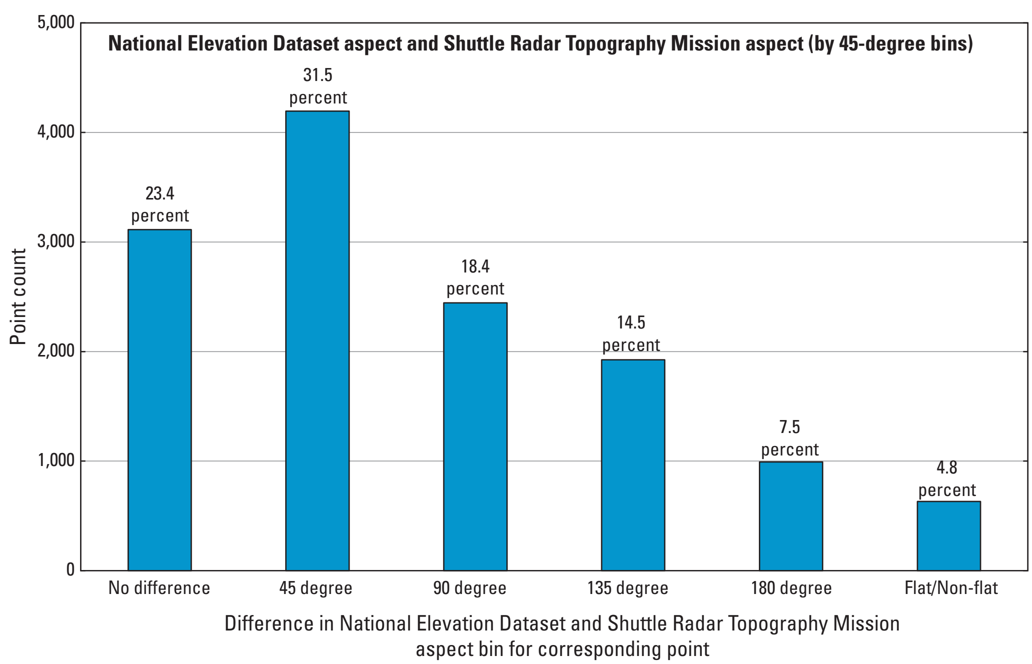

Figure 6. Corresponding aspect values derived from the National Elevation Dataset (NED) and Shuttle Radar Topography Mission (SRTM) data can vary substantially between the two datasets.

Conclusion

Because topographic information is a fundamental requirement for so many Earth science studies and operational geospatial applications, the NED has attained broad usage by the geospatial data user community. An important part of supporting scientific and operational use of the NED is provision of thorough dataset documentation including data quality and accuracy metrics. This document provides such information that leads to more informed use of the NED. When fundamental geospatial data such as that contained in the NED are thoroughly assessed and documented, then the data can be more appropriately applied with increased confidence in the resulting findings and conclusions.

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Publishing support provided by:
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Gesch and others—**Accuracy Assessment of the U.S. Geological Survey National Elevation Dataset**—Open-File Report 2014–1008

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20141008