ACCURACY COMPARISON OF THE SRTM, ASTER, NED, NEXTMAP® USA DIGITAL TERRAIN MODEL OVER SEVERAL USA STUDY SITES

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ABSTRACT

Accurate digital terrain models (DTMs) are necessary for a wide variety applications. National-scale medium-resolution elevation data have been acquired for the conterminous United States under the USGS National Elevation Data (NED; 10 m and 30 m), the Shuttle Radar Topographic Mapping (SRTM; 30 m), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; 30 m) programs. Intermap's STAR technology offers an improvement over the NED and SRTM datasets with its high-resolution (5 m) bare-ground and first-surface elevation data and coincident orthorectified radar imagery over the conterminous United States and 17 Western European countries. SRTM, ASTER, NED and NEXTMap® elevation data over several study sites across the United States were compared to *in-situ* barren land elevation measurements and National Geodetic Survey (NGS) verification check points. The range of study sites represent various terrain types (slope range 0° - 30°) and continental environments (arid, semiarid, and temperate). The NEXTMap® DTM received an overall accuracy of **2.94** RMSE for 808 topographic *in-situ* and NGS - VCPs taken on slopes ranging from 0- 28°, with one half of those being beneath vegetated canopy and obstructed areas (urban). Lower overall DTM accuracies were achieved by the NED (4.52 m RMSE), SRTM (15.27 m RMSE), and ASTER (18.52 m RMSE). All the DTM data sets' accuracy vary with land cover categories ranging from 1.24 m – 16.60 m RMSE (Grass/Shrub), 1.53 m – 41.10 m RMSE (deciduous), 3.20 m – 24.76 m RMSE (evergreen), and 2.13 m – 18.81m (mixed forest).

Key words: NEXTMap®, DTM, NED, SRTM, Elevation, Accuracy

INTRODUCTION

Digital elevation models (DEMs) are topographic models of the Earth's terrain (bare ground) that have had the heights of vegetation, buildings, and other cultural features digitally removed. DEMs are commonly referred in the remote sensing world as digital terrain models (DTMs) typically offered as a continuous elevation surface as a grid (Podobnikar, 2009). Different techniques for the generation of DTMs have been developed since their inception more than fifty years ago (Miller and Laflamme, 1958; Gesch et al., 2002; Hirano et al., 2003; Maune, 2007; Intermap, 2009). Significant advances in remote sensing technologies have led to a new era of higher quality global topographic observations, where reliable topographic measurements are becoming a possibility (Homer et al., 2007). At small scales, spaceborne systems (coarse ground sampling distance (GSD)) such as shuttle radar topographic mission (SRTM) collected 80% of the earth's landmass with 30 m or 90 m resolution (Rabus et al., 2003). At medium scales radar interferometric techniques (medium to high resolution) had been applied to generate global DTMs (Madsen et al., 1993; Farr and Kobrik, 2000; Maune, 2001: Walker et al., 2007; Intermap, 2009). For larger scales and more local usage, airborne laser scanning (LiDAR) and aerial photogrammetric techniques (high spatial resolutions) have been applied to create DTMs (e.g. Lefsky et al., 2002; Næsset, 2002; Andersen et al., 2006). Remote sensing and GIS applications of DTMs have become widespread. Forest and water resource management applications, including watershed management, flood hazard mapping, timber harvest, and fire management are dominant users of DTMs. Terrain attributes often provide direct inputs for environmental, forestry, topographic and hydrological models and thus accuracy of the elevation models is critical to environmental modeling (Kellndorfer et al., 2004; Thirion et al., 2006; Balzter et al., 2007a; 2007b; Anderson et al., 2008). Mapping standards have tended to accept the data if it is within mapping standards such as the National Standard for Spatial Data Accuracy (FGDC, 1998) and the National Digital Elevation Program (NDEP, 2004). However, with a proliferation of DTMs being generated from a host of airborne and spaceborne platforms and technologies, quality assessment of DTMs are a critical parameter for DTM production and various applications. Common techniques for the assessment of DTMs tend to be based on the statistical comparison of small reference areas of higher quality with the created DTM in order to find outliers. The higher the resolution of the DTM, the more difficult the evaluation of input data quality and the assessment of the resulting DTM are. In contrast, visual accuracy assessment methods are generally neglected despite their potential for improving DTM quality. It is suggested that applying visual methods in addition to the more objective statistical methods would result in a more efficient improvement of the quality.

NEXTMap DTM Accuracy Assessment

Mercer (1998) summarized four studies undertaken to assess the vertical accuracy of the NEXTMap DTM. These studies found that over flat bare ground the RMSE was in the order of 1.3-1.5m, while it was 1.7 m on slopes (up to ± 35°), and 1.6-2.2m on mixed terrain (flat and moderately sloped terrain up to 35°). The full range of RMSE was between 0.8-2.2m. The NEXTMap vertical accuracy of the DTM was tested against higher resolution LiDAR over a number of land cover types (Wang *et al*., 2001; Mercer, 2001.). These studies found that over bald areas and flat areas, the DTM achieved an accuracy of 0.68 m RMSE. However, in areas of moderate mountain conditions (no specification supplied by Intermap) the RMSE for the DTM was 1.33m (Wang et al., 2001; Mercer, 2001.). When tested in areas of forests, they found a RMSE of 3.16 m for the DTM and concluded that this was primarily due to the bald-Earth interpolation procedure not handling these areas appropriately, and that the forest areas were contributing to the error (Mercer, 2001). When the forest was masked out the RMSE was found to be 2.19 m (Wang *et al.,* 2001). The Intermap DTM has been validated against GPS and LiDAR measurements in other studies and has been found to be accurate to within 1.013 m RMSE (Fischer and Tate, 2006). The NEXTMap DTM was assessed in the UK by UCL (Dowman and Fischer, 2003: Downman et al., 2003). It was found that when comparing the DTM with photogrammetric checkpoints, the RMSE was 0.834 m. When compared to aerial photography over a bare field, the RMSE was 0.172 m. The DTM was also compared with a LiDAR DTM, with a resulting RMSE of 1.013 m. Detailed GPS measurements were compared to the DTM measurements, and it was found that over mixed terrain (hilly, flat) along a road a RMSE of 1.67 m was obtained. When photogrammetric check points were used on bare earth in open areas, a RMSE of 0.834 m was obtained. Tighe (2003) summarizes three assessments (in addition to the study be Dowman et al. discussed above) of the vertical accuracy after the sensor upgrade. Studies carried out by the USGS with data with a stated accuracy of 3 m over moderate to flat terrain concluded that a RMSE of 1.2 m was achieved. A similar study over a different test site concluded that a mean offset of 0.1 m was present in the data. The UK Environment Agency reported a RMSE of 0.78 m when compared to LiDAR data (Tighe et al., 2003). In summary, the vertical accuracy of the DTM may be as good as 0.5m RMSE over flat, un-vegetated terrain but up to 2 m on moderate slopes. Li et al., (2004) stated that ‘it has been found that at 5-m point spacing, 1 - 2 m DTM vertical RMSE accuracy can be routinely achieved in moderate terrain.

NED DTM Accuracy Assessment

In 1999, and for the first time, the NED was assembled completely for the continental United States from 7.5-min DEM source data (10 m and 30 m GSD; Gesch et al., 2002). The 7 m RMSE accuracy is a the production goal described in the USGS Data Users Guide 5—Digital Elevation Models, last published in 1993 and traditionally known by many users as the “blue book” which states a 7 m vertical RMSE accuracy of USGS 7.5-minute DEMs or the NED data (U.S. Geological Survey, 1997). This version of the NED was tested by comparison with the Global Positioning System (GPS) points was the 1-arc-second layer released in June 2003, which was the last version assembled completely from USGS 10 m and 30 m 7.5-minute DEMs. Since that time, some areas have been updated analysis based on high-resolution LiDAR or photogrammetric data, which may have even better accuracy than the quadrangle-based USGS DEMs. In an effort to provide more information to users on the vertical accuracy of the NED, the data set has been tested by comparing it with the geodetic control points that the National Geodetic Survey (NGS; Smith and Roman, 2001; National Geodetic Survey, 2003). The distribution of this set of more than 13,000 high-precision survey points across the entire NED data set. The overall absolute vertical accuracy expressed as the root mean square error (RMSE) is 2.44 m.

SRTM DTM Accuracy Assessment

The SRTM radar signal measurement result in a reflective surface elevation which depends on terrain cover and is a complicated function of the electromagnetic and structural properties of the scattering medium (Bhang et al., 2007). In snow, the penetration depth of the radar signal depends on wetness, temperature, and porosity (Braun et al., 2007). Vegetation presents an even more complex scattering environment. It has been estimated that C-band only penetrates a quarter or a third of the canopy height (Carabajal, 2005). Performance evaluations by NIMA, the USGS, and the SRTM project team have shown the absolute vertical error to be much smaller, with the most reliable estimates being approximately 5 m (Rosen et al., 2001; Sun et al., 2003). Brown et al. (2005) used GPS and NED data to evaluate the accuracy of the SRTM data for southeastern Michigan. They reported that the SRTM mission specifications for absolute and relative height errors for the GPS ground control point targets were exceeded. A more extensive analysis of the SRTM DGPS data indicates that it meets the absolute and relative accuracy requirements even for bare surface areas. Previous research efforts indicated that accuracy for an IFSAR derived DTM could be terrain dependent. According to the mission objectives, SRTM data were expected to have an absolute horizontal circular accuracy of less than 20 m. Absolute and relative vertical accuracy was anticipated to be less than 16 and 10 m, respectively (Kellendorfer et al., 2004).

ASTER DTM Accuracy Assessment

As part of ASTER digital elevation model (DEM) accuracy evaluation efforts by the US/Japan ASTER Science Team, stereo image data for four study sites around the world have been employed to validate prelaunch estimates of height accuracy (Hirano et al., 2003). Automated stereo correlation procedures were implemented using the Desktop Mapping System (DMS) software on a personal computer to derive DEMs with 30 to 150 m postings. Results indicate that a root-mean-square error (RMSE) in elevation between ±7 and ±15 m can be achieved with ASTER stereo image data of good quality. An evaluation of an ASTER DEM data product produced at the US Geological Survey (USGS) EROS Data Center (EDC) yielded an RMSE of ± 8.6 m. Overall; the ability to extract elevations from ASTER stereopairs using stereo correlation techniques meets expectations. Studies were conducted by a large group of international investigators, working under the joint leadership of U.S and Japan ASTER Project participants, to validate the estimated accuracy of the new ASTER Global DEM product and to identify and describe artifacts and anomalies found in the ASTER GDEM (ASTER, 2009). They reported an overall vertical RMSE for the 934 1^{o} X 1^{o} GDEM tiles of 10.87 meters, as compared to NED data; which would equate to a an accuracy at 95% confidence of 21.31 meters, or a little more than the 20 m accuracy at 95% confidence estimated for the ASTER GDEM prior to its production. Vertical accuracy of NED data is approximately 2-3 m RMSE. When compared with more than 13,000 GCPs the RMSE dropped to 9.35 meters. These values convert, respectively, to vertical errors of just over and just under the estimated ASTER GDEM vertical error of 20 meters at 95% confidence. The ASTER (2009) found the ASTER DTM to contain significant anomalies and artifacts, due to clouds and the algorithm used to generate the final GDEM, which will affect its usefulness for certain user applications. Another shortcoming of the current ASTER GDEM Version 1 is the fact that no inland water mask has been applied. Consequently, the elevations of the vast majority of inland lakes are not accurate, and the existence of most water bodies is not indicated in the ASTER GDEM. The vertical accuracy of this ASTER DEM was checked against 40 DGPS survey points and 12 points digitized from USGS 1:24,000-scale topographic quadrangles, yielding an RMSEz of ±8.6 m. This generally corresponds with other validation results reported by EDC (EDC DAAC, 2001).

Objective

The overall objective of this paper is to perform an accuracy assessment of two airborne and two spaceborne remotely sensed DTMs against *in-situ* and national geodetic survey (NGS) data to see how well the various DTMs perform over a variety of land cover types and a range of sloped terrain.

DATA AND STUDY AREA

Study Areas

Six study sites located in the United States of America (Arizona (1), Minnesota (2), Colorado (1) and California (2)) were selected for this research. There are several reasons for selecting six study sites. First, the bio-geophysical characteristics of each study site provide a unique opportunity to evaluate DTM data across a range of vegetation densities and structural classes as well as a variety of topographic conditions and environments (arid, semi-arid, temperate and boreal). The adoption of six study sites also facilitates the examination of the regional applicability of the DTM data sets for a range of environmental conditions.

Arizona Study Site

The Arizona study site was chosen to represent an undisturbed natural arid environment consisting of a diverse range of vegetation classes over flat to steep terrain. The study site is located in south-eastern Arizona, near the Mexican border (Figure 1). Geographically, the region is located approximately between $31^{o}45'09''$ N and $31^{o}22'50''$ N latitudes and $111^{o}37'42''$ W and $111^{o}14'53''$ W longitudes. It covers an approximate area of 1484 km^2

which is predominately consisting of grassland, shrub/scrub, and evergreen forests, with minor amounts of wetlands, bare earth and urban development. Altitude ranges from 932 m in the plains to 1750 m in the mountains (range ~ 818 m).

Minnesota Study Sites (2)

There are two study sites in Minnesota. The first, Ely, is a city in St. Louis County, Minnesota, USA was chosen to represent dense homogenous coniferous and deciduous and heterogeneous mixed forests with little understory in a temperate environment. It is situated in the Vermilion Iron Range (Figure 1). Geographically, the region is located approximately between 47°52'30" N and 47°37'30" N latitudes and 91°52'30" W and 91°37'30" W longitudes. The study site covers an area of 169.8 km^2. Glacial ice moved from west to east across the subsection, deepening stream valleys in the bedrock. Long, east-west oriented lakes now occupy these enlarged valleys (Dept. of Soil Science, Univ. of Minnesota 1981b). The topography of this site is dominantly rolling with irregular slopes (0°-18.7°) and many craggy outcrops of bedrock. The elevation range of this site is 422 – 506 m (delta of 94 m). Most of this site is forested with red (*Pinus resinosa*) and white pine (*Pinus strobus*), Douglas fir (*Pseudotsuga menziezii*), black spruce (*Picea mariana*) and red maple (Acer rubrum). The second, International Falls, was also chosen to represent dense homogenous coniferous and deciduous and heterogeneous mixed forests with little understory in a temperate environment. The International Falls site covers a region approximately 16.35 km^2. Geographically, the region is located approximately between 48°37'30" N and 48°30'00" N latitudes and 93°30'00" W and 93°15'00" W longitudes (Figure 4). The elevation grades from 335 m in the northwest corner to 365 m east. The site sits on a lake plain with slopes less than 1.0°. The site is dominated by white pine (*Pinus strobus*), white spruce (*Picea glauca*), and balsam fir (*Abies balsamea*) conifers. The eastern portion was dominated by white pine, red pine (*Pinus resinosa*), and jack pine (*Pinus banksiana*) forest.

Colorado Study Site

The study site focuses on a 180 km^2 area located near the town of Morrison Colorado, USA. It was selected because it represents a semi-arid environment and contains the three land cover types of interest (barren, shrub/scrub, and evergreen forest; Table 1). There are some gentle hills that are interspersed with boulders and open rock surfaces. The topography of this site is dominantly rolling with irregular slopes (0°-46.5) and many outcrops of bedrock. Geographically, the region is located between 39°45'09" N and 39°37'20" N latitudes and 105°06'36" W and 105°15'55" W longitudes. Altitude ranges from 1660 m in the foothills to 2435 m in the mountains. The region consists of the Rocky Mountain Range running NW – SE located along the left side of the imagery with residential and commercial areas located in the eastern section (Figure 1). An extensive transportation network is present. Forests are dominated by evergreen and occur mainly on the west facing slopes whereas shrubs occur mainly along the east facing slopes. The region also contains urban, suburban, grassland, and deciduous land cover.

California Study Sites (2)

There are two study sites in California. The first, San Luis Obispo County study area, consists of 148 vertical checkpoints spread throughout the county, which is 8, 557 km^2 in size. It lies on the California coast between the major urban areas of Los Angeles and San Francisco. There are several small urbanized areas, however they are relatively small in size and centered along the coast. This county was chosen due to its wide variety of land cover types, as they range from urban along the coast to grasslands, wetlands, and evergreen forest in the higher elevations of the Santa Lucia Range. There is also a significant amount of agricultural areas spread throughout the county, specifically vineyards. Geographically, San Luis Obispo County lies from roughly 34º 54' 13" to 35º 47' 32" N, and 119º 28' 21" to 121º 20' 16" W. Elevations at the VCPs ranged from around 1m along the coast, to over 1,770 m in the higher elevations of the county. Agriculture, urban, sand dunes, and grasslands cover most of the eastern/coastal regions of the county, while the central portions of the county are mountainous with significant evergreen forest and shrub. The eastern sections of the county have less terrain relief and consist primarily of grassland (The Carrizo Plain) and agriculture. Some wetlands are also in the Carrizo Plain, which lies in the eastern portion of the county. The second, Riverside County study area, consists of 147 vertical checkpoints spread throughout the county, which stretches from east of Los Angeles to the Colorado River, which flows along the border with Arizona. Riverside is a relatively large county, with an approximate size of 18,667 sq km. It lies from 114º 26' 11" to 117º 40' 29"W, and from 33º 25' 38" to 34º 04' 33" N. Desert occupies most of the county, as parts of the Mojave and Colorado deserts lie within Riverside County. Apart from desert, there are some small areas of evergreen and shrub in the highest elevations of the Santa Rosa Mountains, as well as some agriculture located along the Colorado River in the easternmost portion of the county. The western portion of the county features rolling hills and significant urbanization, while the central regions are hilly or mountainous with scattered development and a primarily arid/desert climate. The main urban areas within the county are Riverside, Moreno Valley, and Corona, all of which lie in western Riverside County. Elevations at the VCPs range from below sea level (-67 m) in the desert areas, to 2654 m in the mountainous regions.

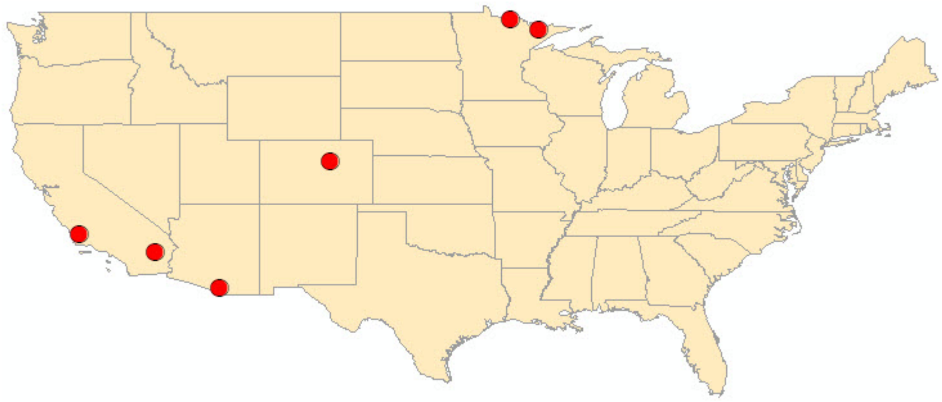

Figure 1. Study sites (California [2], Arizona [1], Colorado [1], and Minnesota [2]).

Table 1. Land cover classes and their description (Modified after Homer et al., 2007).

Land Cover	Class Description modified from NLCD (Homer et al., 2007)
Barren Land	Barren areas of bedrock, desert pavement, volcanic material, sand dunes, strip mines, gravel pits, and other earthen material. Vegetation accounts for <15% of total cover.
Grassland	Areas dominated by herbaceous vegetation, grasses, production of annual crops, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops generally greater than 80% of total vegetation.
Shrub	Areas dominated by shrubs; <5 m tall with shrub canopy typically >20% of total vegetation. This class includes true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions.
Deciduous	Areas dominated by trees generally >5 m tall, and >20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
Evergreen	Areas dominated by trees generally > 5 m tall, and > 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year.
Mixed	Areas dominated by trees generally >5 m tall, and >20% of total vegetation cover. Neither deciduous nor evergreen species are >75% of total tree cover.

Data

Four remotely sensed DTM data sets were chosen for comparison to the GCPs collected in the field (Table 1). These were chosen to represent four DTM data availability scenarios.

Table 2. DTM data sources.

Source	NEXTMap, Intermap	NED, USGS	SRTM, NASA	ASTER, METI
Collection Method	Interferometry	Photogrammetry	Interferometry	Photogrammetry
Platform	Airplane	Airplane	Shuttle	Satellite
Ground Sampling Distance	5 m	10 m	30 m	30 m
Published Accuracy RMSE	1 m	2-3 m	16 m	20 m
Reference	Intermap, 2009	Gesch, 2007	Rabius, 2003	ASTER, 2009

NEXTMap® Elevation Data

Intermap Technologies is a Canadian-based company that commercially operates several airborne single-pass across-track interferometric synthetic aperture radar (IFSAR) 3 cm wavelength (X-HH) sensors mounted in airborne platforms (e.g., King Air, Learjet 36) which collect nationwide elevation data and imagery (Intermap, 2009; Mercer, 2004; Tighe et al., 2009). Data from these IFSAR platforms are called NEXTMap. The NEXTMap® data were interferometrically processed by Intermap using a proprietary IFPROC processor. The processor included averaging of multiple data takes (from overlapping flight lines and tie lines), where possible, and filtering of the interferogram to reduce phase noise and smoothing during final processing. The NEXTMap data utilized in this study consists of digital terrain model (DTM), processed in 7.5-minute tiles according to the USGS index. The DTM is derived from the DSM by experienced editors using Intermap's semi-automated proprietary three dimensional IFSAR editing software and a set of edit rules described in the Intermap Product Handbook (Intermap, 2009). The NEXTMap® DTM data are processed to 32-bit floating 5 m GSD in grid format using a WGS84 datum with geographic coordinates. The data have 1 m vertical and 2 m horizontal RMSE accuracy in regions of flat to moderate slope in unobstructed terrain (Intermap, 2009).

United States National Elevation Data (NED))

The U.S. Geological Survey (USGS) produced the National Elevation Dataset (NED) by merging the highest-resolution, best-quality elevation data available across the continental United States, Alaska, Hawaii, and the island territories into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale digital elevation model (DEM) data for the conterminous United States and 1:63,360-scale DEM data for Alaska. NED has a consistent projection (geographic), resolution (1 arc second), and elevation units (meters; Osborn et al., 2001). The accuracy of the NED varies spatially because of the variable quality of the source DEMs. As such, the NED "inherits" the accuracy of the source DEMs. Some accuracy statistics are available in the source DEM headers, and this information is captured in the spatially referenced metadata. This accuracy information has limited usefulness because it is a relative measure of how well the DEM fits the source material from which it was generated (Gesch et al., 2007). Ten meter GSD NED data were obtained from the United States Geological Survey (USGS) website (http://ned.usgs.gov/) for the study sites.

Shuttle Radar Topographic Mission (SRTM) Data

The Shuttle Radar Topography Mission (SRTM) was flown on board the Space Shuttle Endeavour during mission STS-99 February 11-22, 2000. Additional details of the SRTM data are found in (Farr and Kobrick, 2000; Kellendorfer et al., 2004). 99.97% of the targeted land mass was mapped with at least one data pass (i.e., one Shuttle overpass), 94.59% with at least two data passes, 49.25% with at least three data passes, and 24.10% with at least four data takes. The SRTM dataset was developed from raw radar echoes into digital surface models (DSM), which are available at 1 arc second resolution (30 m ground sampling distance) for the study site (Wagner et al., 2003; USGS, 2006). The SRTM is projected into a geographic coordinate system (GCS) with the WGS84 horizontal datum and the EGM96 vertical datum (USGS, 2006). Voids, or no data holes, in SRTM data are attributed to the complexity of IFSAR technology and topographic shadowing from dense vegetation. The quality of the SRTM data may suffer from mast motion and phase noise errors (Mercer et al., 2004; Becek, 2008). The USGS and the Consultative Group on International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI) distribute processed versions of SRTM data. Interferometric Terrain Height Data 1 (DTHD-1) specifications, which include a 30 m GSD, 16 m absolute vertical height accuracy, and 16 m absolute horizontal accuracy and at the same mapping projection (WGS84), were obtained for the study sites in grid format (Rabus et al., 2003).

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an advanced multispectral imager that was launched on board NASA's Terra spacecraft in December, 1999. ASTER covers a wide spectral region with 14 bands from the visible to the thermal infrared with high spatial, spectral and radiometric resolution. An additional backward-looking near-infrared band provides stereo coverage that has been utilized to derive a world wide global digital elevation model (GDEM). The GDEM imaged the Earth's landmass between 84N and 84S latitudes offering greater coverage over the Shuttle Radar Topographic Mission (described in section 2.3.3). The GDEM was created by stereo-correlating the 1.3 million scenes using bands 3N (nadir-viewing) and 3B (backward-viewing) of an ASTER Level-1A image acquired by the Visible Near Infrared (VNIR) sensor (Pryde et al., 2007). It is formatted in 1 x 1 degree tiles as GeoTIFF files with a GSD of 30 m. Each GDEM file is accompanied by a Quality Assessment file, either giving the number of ASTER scenes used to calculate a pixel's value, or indicating the source of external DEM data used to fill the ASTER voids. Japan's Ministry of Economy, Trade and industry (METI) and NASA announced the release of the ASTER Global Digital Elevation Model (GDEM) on June 29, 2009. ASTER GDEM for the study sites was downloaded as a 30 m GSD grid elevation model.

METHODS

DTM Data Preparation

The SRTM, ASTER, NED, and NEXTMap DTMs were brought into ArcGIS and Global Mapper software packages to create a layered database such that the ground sampling distance of each of the remotely sensed DTMs were maintained. Slope maps we generated using ARCGIS software. The height and slope at the x-y location given by the reference data (NGS and in-situ field measurements) were extracted from each of the DTMs.

Accuracy Assessment of DTMs Against Reference data

The statistical analysis of the elevation difference (DTM minus Reference – Reference Ground Control) were performed on all land cover classes and over all slopes. Statistics were computed for slope classes in an attempt to model the impact of slope (Miliaresis, 2007) on the remotely sensed DTMs being evaluated. The statistical distributions were modeled on the basis of mean, standard deviation (STD), root mean square error (RMSE) and National Standard for Spatial Data Accuracy (NSSDA). Cumulative percentage plots, a visualization of the error distribution that indicate the absolute vertical difference between the DTMs(s) compared to the reference data were calculated for all DTMs. Results were recorded in Table 3 and Figures 2-5, discussed in the Results and Discussion section.

RESULTS/DISCUSSION

Sloped Terrain

Table 3 shows the error statistics for the four remotely sensed DTMs. The overall absolute vertical accuracy expressed as the root mean square error (RMSE) is 18.64 m (ASTER), 19.35 m (SRTM), 3.44 m (NED) and 2.05 m (NEXTMap). Table 3 also contains the accuracy expressed in terms of the National Standard for Spatial Data Accuracy (NSSDA), which uses a 95 percent confidence interval (FGDC, 1998; Maune et al., 2001). The ASTER and SRTM DTMs are less accurate than those derived from NEXTMap and NED. This is not surprising, given that the ground sampling distance (GSD) is 30 m for ASTER and SRTM, whereas the NEXTMap data and NED data have a GSD of 5 m and 10 m respectively.

Vegetation Cover Type

Summary statistics of the DTM error in each vegetated cover type for all four remotely sensed DTMs are given in Table 4. The RMSE, NSSDA 95%, STD and mean of the error for all DTMs increased with increased vegetation cover (e.g. urban/barren/grass versus deciduous/evergreen/ mixed). These results are consistent with those presented in the literature (Andersen et al., 2005; Mercer 2004, Izzawati et al., 2006; Tighe et al., 2009).

Residual Errors

Cumulative percent error plots (Figure 3) help to visualize what percentage of data (DTM data in all land cover classes and in all terrain slopes) can be expected to meet various accuracies. Cumulative percentage error plots are similar to a percentile/ confidence plot for linear error. Formulas exist for calculating statistics like LE90, 95, 99 but those calculations usually expect a near 0 mean. That is not usually the case so this plot gives us a linear error estimate. The NED and the NEXTMap data track well and indicate that approximately 95% of the data will have a vertical accuracy less than 5 meters. There is a distinct separation between the higher (NEXTMap and NED) and coarser (ASTER and SRTM) ground sampling distance DTMs, as well as a clear separation between the SRTM and the ASTER DTM.

Table 3. Results of accuracy assessment of the remotely sensed DTMs versus the reference data for slopes less than 10^o, slopes greater than 10^o and for all slopes.

DTM	Slope	RMSE (m)	NSSDA (95%) (m)	STD (m)	Mean (m)
ASTER	<10^o	12.91	22.34	8.15	10.02
	>10^o	24.08	41.68	12.69	20.47
	All	18.64	32.26	11.63	14.57
SRTM	<10^o	16.49	28.54	15.93	4.36
	>10^o	21.38	37.00	18.17	11.27
	All	19.35	33.49	17.23	8.05
NED	<10^o	2.52	4.36	2.46	0.47
	>10^o	4.43	7.67	3.76	2.36
	All	3.44	5.95	3.21	1.68
NEXTMap	<10^o	0.79	1.37	0.74	0.28
	>10^o	2.97	5.14	1.84	2.34
	All	2.05	3.55	1.68	1.17

Table 4. Accuracy Assessment of DTMs with field collected GPS GCPs over the three land cover types.

DTM	Land Cover	RMSE (m)	NSSDA (95%) (m)	STD (m)	Mean (m)
Grass & Shrub	ASTER	16.6	28.73	10.4	13.05
	SRTM	12.36	21.39	12.18	3.05
	NED	2.93	5.07	2.86	0.81
	NEXTMap DTM	1.24	2.15	1.20	0.34
Deciduous	ASTER	20.79	35.98	7.91	19.25
	SRTM	25.49	44.12	21.3	14.51
	NED	3.43	5.94	2.98	1.74
	NEXTMap DTM	1.53	2.65	0.26	1.51
Evergreen	ASTER	22.23	38.48	14.76	16.89
	SRTM	24.76	42.85	19.51	15.44
	NED	4.46	7.72	3.73	2.56
	NEXTMap DTM	3.20	5.54	1.66	2.75
Mixed	ASTER	10.03	17.36	10.07	4.42
	SRTM	18.81	32.56	13.87	13.01
	NED	2.13	3.69	0.69	2.04
	NEXTMap DTM	3.69	6.39	2.3	3.06

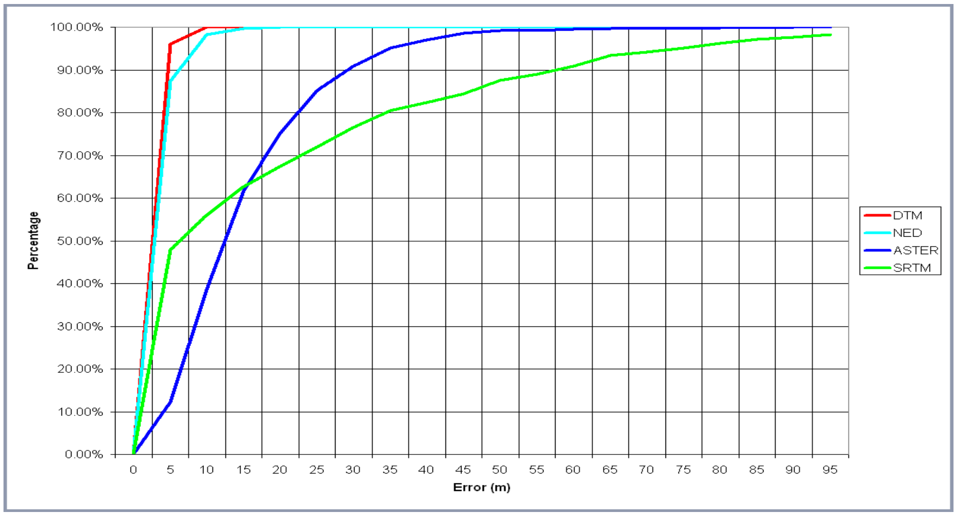

Figure 3. Cumulative percentage plots representing the absolute vertical difference between each DTM and the GCPs for all GCPs collected in terrain of all slopes and over all three land cover types.

CONCLUSIONS AND FUTURE RESEARCH

The extensive ground control (NGS and *in-situ* elevation measurements) allowed for the comparison of the four remotely sensed elevation models (NEXTMap, NED, SRTM and ASTER) in terms of vertical accuracy in various terrain types (flat, rolling, moderate and rugged topography) and land cover types (barren, shrub, deciduous, evergreen, mixed and wetland) of several study sites in the United States. The slope classes and land cover data set (NLCD) were used to categorize the areas in which the DTMs differed. A dense network of control points is also used to categorize the error in each DTM. The patterns of disparity and error are largely as expected given the strengths and weaknesses of the different DTM sources. The research presented here confirms that the quality of the NEXTMap, NED and SRTM DTMs meet published specifications. These results are consistent with previously published results (Rabius et al, 2003; Andersen et al., 2005; Gesch et al., 2007; Intermap, 2009). The SRTM did not, however, perform as well as the evaluations conducted by NIMA, the USGS, and the SRTM project team which have shown the absolute vertical error to be much smaller, with the most reliable estimates being approximately 5 m (Curkendall et al., 2003; Rosen et al., 2001a,b; Smith and Sandwell, 2003; Sun et al., 2003). The NEXTMap DTM has a published accuracy specification of 1 m in slopes less than 10 degrees and in unobstructed areas (Intermap, 2009). The results presented here were not restricted to unobstructed areas and thus could help to explain why the NEXTMap DTM achieved an RMSE at 2.05 m instead of 1 m. With a NSSDA 95% accuracy of 32.26 m, the ASTER data does not meet the published specification (ASTER DEM Evaluation Team, 2009). Perhaps this is due the noise in the autocorrelation methods utilized to derive the DTM product. The accuracy of all the DTMs degrades in regions of slope greater than 10º. The ASTER results thus did not concur with those published by Hirano et al. (2003) who an RMSE in elevation between ±7 and ±15 m or those published by EDC (2001) which yield an RMSEz of $\underline{+}$8.6 m. The slope characteristics of the terrain have significant impact on accuracy of all the DTMs. Accuracy particularly suffers on terrains with slope values higher than 10°. It is clear that the all DTMs exhibit a great deal of sensitivity to vegetation cover. The results presented here suggest that factors such as the purpose of the DTM are often more important than its absolute accuracy. Even if the latter matters most, it depends on how the accuracy is quantified. The impacts of data currency at the time of the data collection were not considered. Future research is underway to address the temporal differences of DTMs and GCPs (GCPs and ASTER - 2009, NEXTMap - 2008, SRTM - 2000 and NED -1974).

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