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Applications of Shuttle Radar Topography Mission Elevation Data

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Abstract

The Shuttle Radar Topography Mission (SRTM) was flown in February 2000 and collected the first ever high-resolution near-global digital elevation data. The final SRTM data have become widely available at 1 arc-second resolution for the United States and 3 arc-second resolution for other areas. This article reviews the background of the SRTM mission, the data quality characteristics of the SRTM elevation data, and the many applications of SRTM elevation data that have emerged in recent years, including forest ecology, volcanology, glaciology, geomorphology, and hydrology. SRTM data have been particularly useful for areas where previously limited topographic data were available, but results from STRM data also compare reasonably well with those obtained from other high-resolution digital elevation models.

Introduction

In February 2000, the Space Shuttle Endeavour flew a single payload 11-day mission to collect near-global high-resolution topographic data. The space flight was designated as the Shuttle Radar Topography Mission (SRTM). Prior to this mission, the only complete global digital elevation dataset available was the US Geological Survey (USGS) GTOPO30 data with 1 km post spacing. Figure 1 provides a visual comparison of SRTM and GTOPO30 topographic information.

The SRTM mission accomplished its original objectives and nearly 12 terabytes of raw radar echo data were collected. Initial elevation data were released within a couple of years of the mission but a final edited SRTM dataset only became available in 2004. Substantial editing of the original SRTM data resulted in major improvements in terms of void filling and the addition of water bodies to the elevation data.

The final SRTM data are now widely available through several Web sites and FTP sites. Data are available at a spatial resolution of 1 arc second for the United States (approximately 30 m) and at 3 arc seconds for the rest of the world (approximately 90 m). Since its release in 2004, the SRTM data have undergone substantial evaluations in terms of accuracy and comparisons

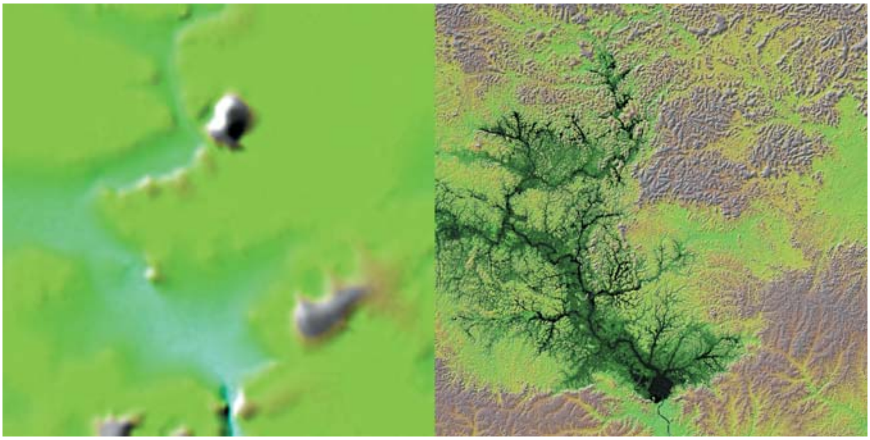

Fig. 1. These two shaded relief images show exactly the same area, Lake Balbina near Manaus, Brazil. The image on the left was created using the best global topographic dataset previously available, the USGS's GTOPO30. In contrast, the much more detailed image on the right was generated with SRTM data. For many parts of the globe, SRTM has provided much more detailed topographic information than previously available. Image courtesy: NASA/JPL.

with other data sources. Many new applications have emerged, in particular, for areas where previously existing data were of much lower accuracy and resolution.

The SRTM data are unique in that never before had the vast majority of the Earth's surface been mapped with a single consistent method in such a short period of time. This has resulted in an unprecedented topographic 'snapshot', giving way to a vast range of novel applications in the geosciences, including several at the global scale. Figure 2 provides an example of the type of visualizations that can be created using SRTM data for nearly anywhere in the world.

This article will review the background of the SRTM mission, the data quality characteristics of the SRTM elevation data, and the many applications of SRTM elevation data that have emerged in recent years, including forest ecology, vulcanology, glaciology, geomorphology, and hydrology.

Topographic Mapping

Conventional topographic mapping has produced maps of uneven quality. Many countries have created national cartographic databases, but topographic maps are at a variety of scales and resolutions, use country-specific datum, and are inconsistent across jurisdictional boundaries. Global coverage has also been uneven, particularly in cloudy parts in equatorial regions, and many countries lack high-quality digital topographic data. Conventional means have proven difficult and expensive to produce a global topographic dataset of consistent scale and resolution (Farr et al. 2007). The emergence

Fig. 2. East-looking view of the US Virgin Islands and British Virgin Islands along the northeast perimeter of the Caribbean Sea. For this view, a nearly cloud-free Landsat image was draped over SRTM elevation data. Shading derived from the SRTM data was added to enhance the topographic expression. Elevation is shown with 1.5× scaled vertical exaggeration. Image courtesy: NASA/JPL.

in the 1990s of synthetic aperture radar (SAR) interferometry has made it possible to efficiently and affordably create a global digital elevation model. The SRTM has demonstrated the feasibility of this approach.

Interferometric SAR, or InSAR, makes uses of phase difference measurements derived from two radar images acquired with a very small base to height ratio to measure topography. Sufficient accuracy is obtained by careful measurement of the baseline height and orientation of the location of the sensor platform relative to the reference coordinate system. Radar wavelengths in the centimeter to meter range provide good signal returns from rough surfaces, such as base ground, rough water, and vegetation. Heavy vegetation canopies, however, many not be penetrated very much, and in those areas the topographic maps will not represent the ground surface very reliably. Very smooth surfaces, such as calm water and even sand, may not scatter enough radar energy back to the sensor to yield a height measurement.

SRTM Space Flight and Design

The origins of SRTM lie in a series of tests of synthetic aperture radar instruments aboard the Space Shuttle starting in 1981. Several design elements, including a foldable antenna and variations in the swath width, were incrementally refined, leading up to the SRTM flown on Space Shuttle Endeavour in February 2000. The mission was a joint project of the National Aeronautics and Space Administration (NASA), the National Geospatial Intelligence Agency (NGA) (formally the National Imagery and Mapping Agency) of the US Department of Defense, and the German Space Agency. SRTM's objective was to acquire a digital elevation model of all land between 60°N and 56°S, covering about 80% of the Earth's land surface. The elevation model was to be sampled over a grid of 1 arc second by 1 arc second (approximately 30 m by 30 m) with a linear vertical absolute height error of 16 m at the 90% confidence interval, similar to the specifications of the 30 m digital elevation models (DEM) that are part of the US National Elevation Dataset (NED).

The SRTM employed two synthetic aperture radars, a C-band system (5.6 cm) and an X-band system (3.1 cm). NASA's Jet Propulsion Laboratory (JPL) was responsible for the C radar, while the German Space Agency was responsible for the X radar. X radar was included as an experimental demonstration to be used as an independent dataset to help resolve problems in C radar processing and quality control.

The Space Shuttle Endeavour was launched with a six-person crew on February 11, 2000. The payload doors were opened and the foldable mast was deployed. The main antennas were located in the payload bay and supplementary receive-only antennas were located on the 60 m long mast (Figure 3).

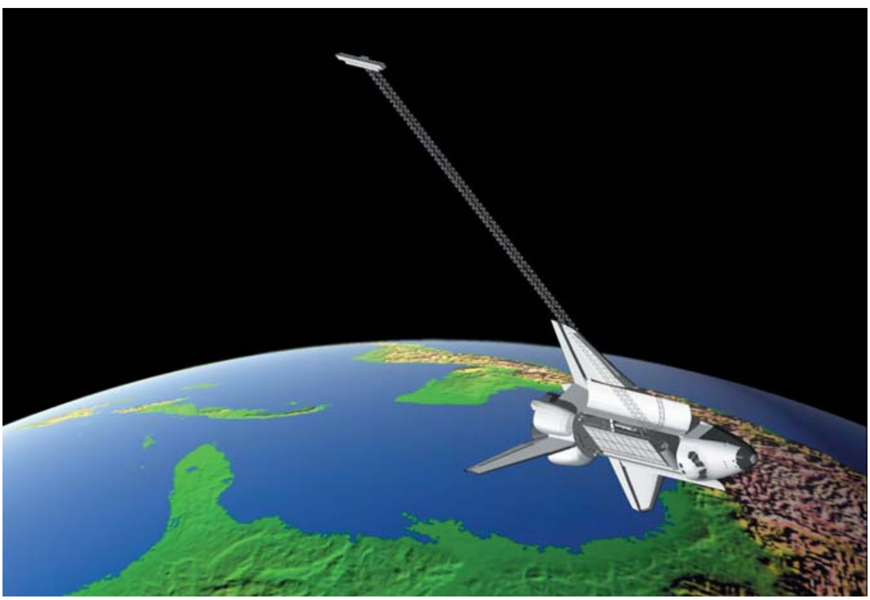

Fig. 3. Computer-generated view of the SRTM mission. The shuttle payload bay contains the main antennas while secondary receive-only antennas are attached to the 60 m long mast. Image courtesy: NASA/JPL.

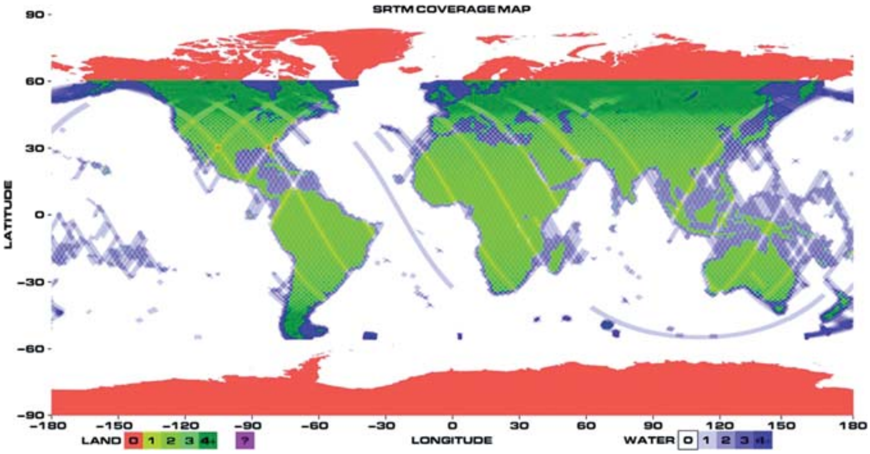

Fig. 4. SRTM coverage map. The colors of the swaths indicate the number of times the area was imaged by SRTM. For land, one-time coverage is green, twice is yellow-green, and so on, as shown in the key at lower left. Over water, the color code is in shades of blue as shown in the key at lower right. Small amounts of data were collected over the water for calibration purposes. Areas in red could not be mapped; of the targeted land approximately 50,000 km^2 could not be mapped, all of which is located in the United States. Image courtesy: NASA/JPL.

Mapping continued for 149 orbits (222 hr) using an imaging swath of 225 km. On-board high-rate data tape recorders were used to record approximately 12 terabytes of data. The radars operated virtually flawlessly. Coverage of the C-band radar is shown in Figure 4. C-band imaged 99.96% of the targeted land mass at least once. Because data for 10 orbits of the 159 required orbits were not recorded correctly, a few patches of land in North America were not included. The X-band imaged approximately 40% of the target area because it collected 50 km swaths with gaps between them. Further details of the mission design can be found in Farr et al. (2007). Data gathering was concluded on flight day 10 and the Space Shuttle returned on February 22, 2000.

Data Processing, Editing, and Distribution

The software for processing of the raw data was broken into three parts: (i) interferometric processor, which converted the raw radar data into a height map and radar image strips; (ii) mosaic processor, which took the myriad of strips from all over the world and compiled a mosaic of the height and image data one continent at a time; and (iii) verification system, which tested the mosaics for quality, producing an accuracy map. Processing took several years to complete, after which initial research-grade elevation products were released. Since then, NGA has edited the SRTM data, which consisted of delineating and flattening water bodies, better defining coastlines, removing 'spikes' and 'wells', and filling small voids.

The resulting data are referred to as the 'finished' SRTM data and have been made available by NGA public release. A much more detailed description of the processing of the SRTM data is provided by Slater et al. (2006).

At present, 1 arc-second SRTM data are only available for public for the United States but NASA and NGA are trying to work out a policy allowing access to 1 arc-second SRTM data for the rest of the world. A by-product of the finishing process is a vector shoreline database, the SRTM Water Body Dataset, which was produced by NGA and includes ocean coastlines, lake shorelines, and rivers. This dataset has been released at full resolution for public use. The principal distribution mechanism for the SRTM data is the Earth Resources Observation and Science Center of the USGS, but several other international agencies have also made the finished SRTM data products available for download.

Data Quality Characteristics

VERTICAL ACCURACY

The SRTM data products have undergone extensive validation by both JPL and the broader research community. As part of the internal data validation, JPL compared SRTM elevations with ground control point at a continental scale. Complete details are reported in Rodriguez et al. (2005, 2006). In brief, long tracks of kinematic global positioning system estimates of elevation were acquired along roads on all continents. These control data were determined to be accurate to better than 1 m vertical and have allowed for a characterization of SRTM errors on a range of spatial scales. The absolute vertical accuracy for the continental datasets is estimated at 9 m or better based on the 90th percentile of the error distribution, which clearly met the stated accuracy goal of 16 m. Figure 5 shows the spatial pattern of the absolute vertical error by continent. The greatest errors are associated with steep terrain, primarily as a result of the horizontal error.

In addition to the internal validation by JPL, many other researchers have reported on the data quality characteristics of the SRTM data. While generally in agreement with the findings by Rodriguez et al. (2005, 2006), these complementary studies vary in their geographic coverage, source of control data, and quality characteristics examined.

Several researchers have employed satellite-based radar or laser altimetry to validate the SRTM data. Berry et al. (2007) used satellite radar altimetry from ERS-1 and Environmental Satellite (Envisat) and found strong agreement with the SRTM data, with global statistics for mean difference of 3 m and standard deviation of 16 m. Fusion of the SRTM and ERS-1 data is suggested as a way to reduce data voids and remove the effects of forest canopy. Bhang et al. (2007) compared SRTM data with laser altimetry form the Ice, Cloud and land Elevation Satellite (ICESat). While generally

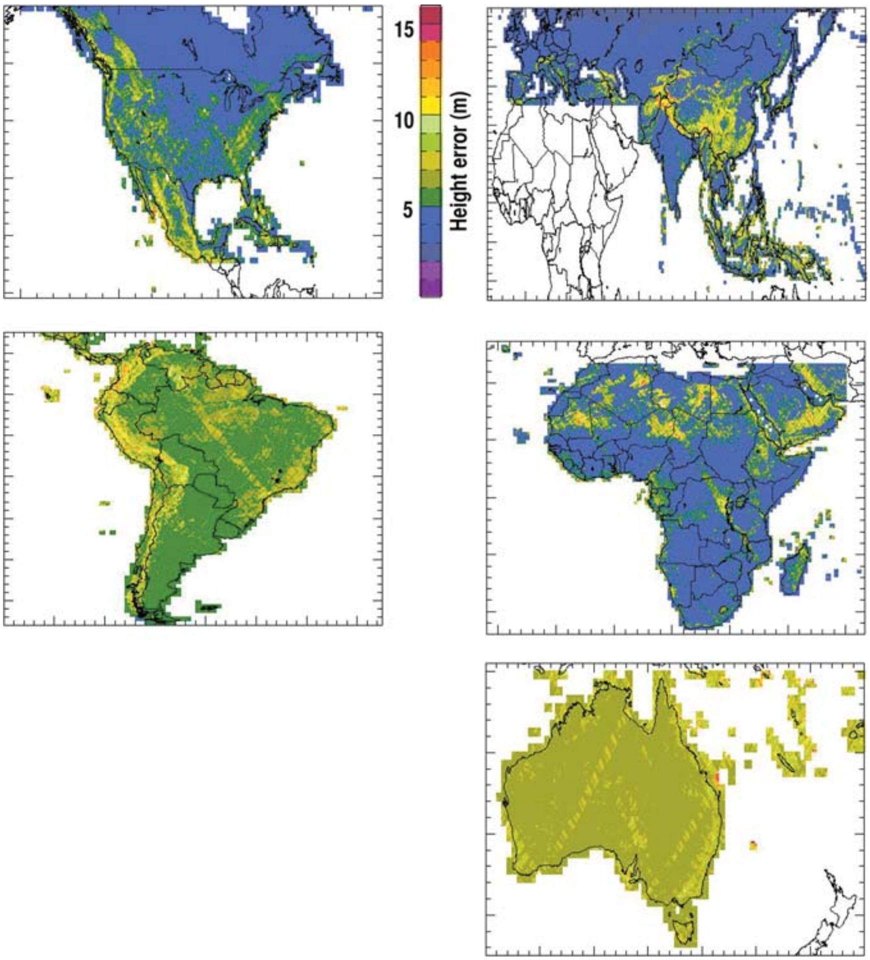

Fig. 5. Absolute vertical error of STRM data by continent. The 90th percentiles are: 5.6 m for Africa, 6.0 m for Australia, 6.2 m for Eurasia, 9.0 for North America and 6.2 for South America. Image courtesy: NASA/JPL.

in good agreement, differences between SRTM and ICESat were found to be largest in areas of high relief and with substantial forest cover. The SRTM elevation data have also been validated using results from the earlier Shuttle Laser Altimeter-02 (SLA-02) collected in 1997 (Sun et al. 2003).

Other sources of elevation data have also been used to validate the SRTM data, including airborne laser altimetry, ground control points, and traditional cartographic DEMs (Bourgine and Baghdadi 2005; Brown et al. 2005; Falorni et al. 2005; Gorokhovich and Voustianouk 2006; Shortidge 2006). Results generally confirm the findings from JPL: SRTM data have a vertical accuracy that exceeds the original data specifications,

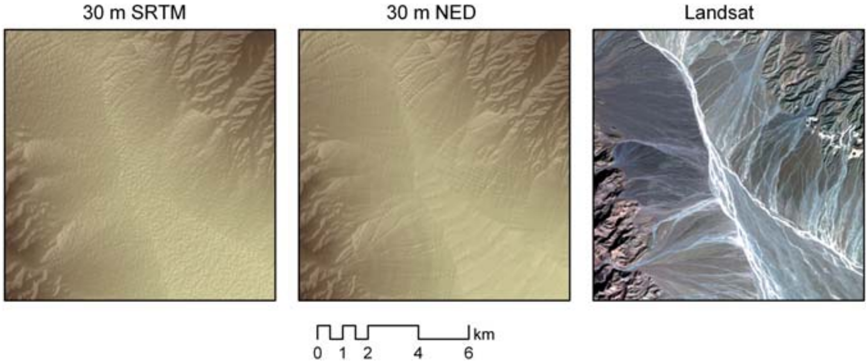

Fig. 6. Hillshaded elevation model of a small part of Death Valley in the United States. The SRTM data reveal a substantial amount of speckle noise. The NED elevation model is much smoother, although some of the artifacts of interpolation from contours are visible.

vertical error is highest in areas of high relief and strongly correlates with slope, and elevation is typically overestimated, in particular in forested areas.

For the areas where X-band SRTM data were collected both C- and X-band DEMs are available. The vertical accuracy of the C- and X-band DEMs is very similar and an optimal algorithm for merging the two DEMs has been developed (Hoffman and Walter 2006). Results suggest that a merged DEM presents an improvement above either of the original DEMs in terms of both completeness and accuracy.

SPECKLE NOISE

One common characteristic of SAR DEMs like SRTM is the presence of a substantial amount of speckle noise, that is, seemingly random vertical noise (Falorni et al. 2005). Speckling has the effect of increasing slope estimates at short distances. Several researchers have noted large slope values from SRTM DEMs compared to DEMs from other sources at the same resolution (Alsdorf et al. 2007a; Falorni et al. 2005; Guth 2006; Kiel et al. 2006). In general, speckling has a negative effect on hydrological and geomorphological applications of SRTM data, in particular, in areas of low slopes. Figure 6 shows an example of a study site in Death Valley which is completely free of any vegetative cover. In this case, the SRTM data represent a bare-earth DEM, and reveal a fair amount of noise relative to a DEM obtained from NED at the same resolution.

Falorni et al. (2005) have shown that much of the speckling can be removed using a wavelet filter, although further fine tuning of the filter is needed. Refinement of the SRTM data using Kriging interpolation has also been shown to reduce the effects of random vertical noise (Valeriano et al. 2006).

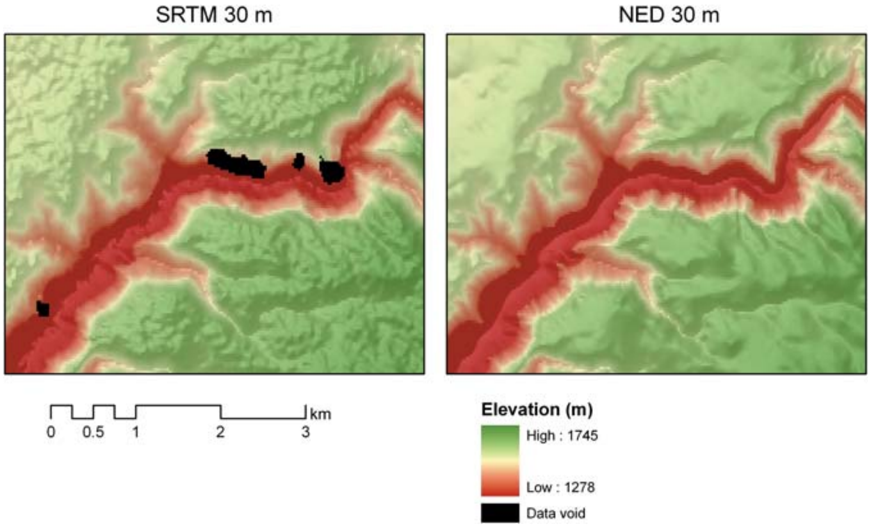

Fig. 7. Hillshaded elevation model of a small part of the Grand Canyon in the United States. SRTM elevation data are shown on the left and NED elevation data are shown on the right. The SRTM data reveal a number of typical voids (shown in black) on steep slopes.

VOIDS AND VOID FILLING

Areas of extreme error or from which no radar signal returned were given a void value in the SRTM-finished data products. Voids were caused by two mechanisms: steep slopes facing away from the radar (shadowing) or toward the radar (layover), and smooth areas such as water or sand which scattered too little energy back to the radar to create an image.

Figures 7 and 8 show examples of voids. Figure 7A shows a small portion of the Grand Canyon with several voids in the SRTM elevation data on the northern slopes of a steep canyon wall. Figure 7B shows the NED DEM for the same area. Figure 8 shows a portion of the Perito Moreno glacier on the border of Chile and Argentina with many substantial voids resulting from shadowing and layover.

The widespread occurrence of data voids presents an ongoing challenge for SRTM data users. For the conterminous United States, Hall et al. (2005) determined that data voids amount to 0.3% of the total area and are found more often on steep slopes that face south. More than half of these voids were found to consist of six or fewer connected pixels. The largest data voids were associated with water bodies, while the rest is explained by terrain-radar interaction characteristics. In a global assessment of the SRTM data, Reuter et al. (2007) identified approximately 3.3 million data voids covering approximately 800,000 km^2. Voids were found to be very common in mountainous areas, as well as in very flat areas dominated by sand (e.g. Sahara).

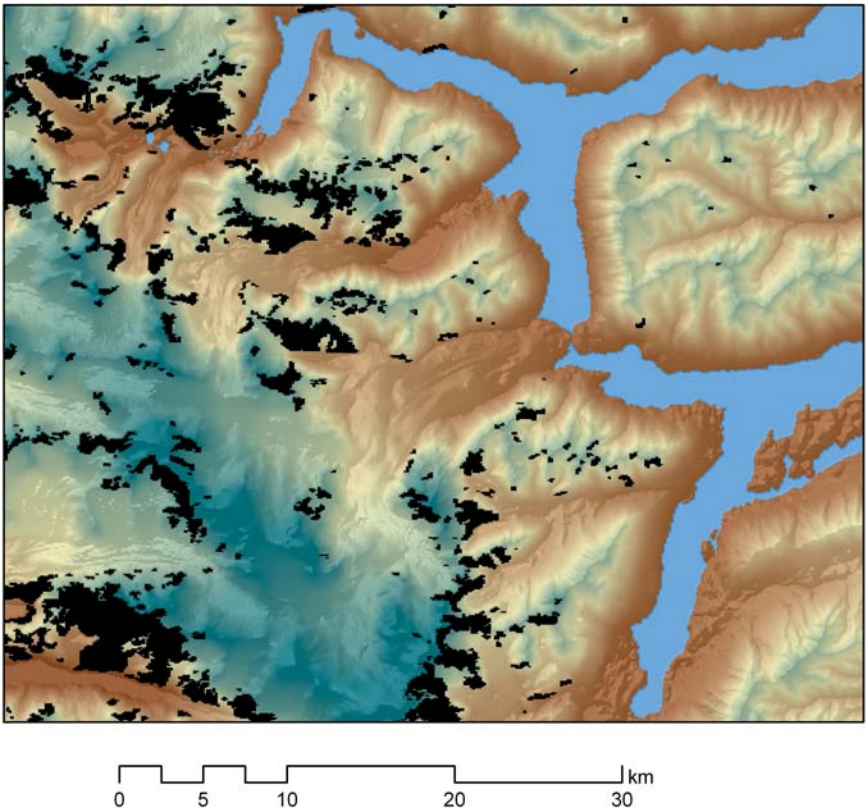

Fig. 8. Hillshaded elevation model of a small part of the Perito Moreno glacier on the border of Chile and Argentina. The SRTM data reveal a large number of voids (shown in black) in the areas of greatest relief. The elevation data for the lake (Lago Argentina, shown in light blue) do not reveal any voids due to the substantial editing of the original SRTM data. As a result, the elevation values within the lake are perfectly identical across its entire extent. The boundaries of such waterbodies are available as a separate dataset, the SRTM Water Body Dataset (WBD).

While the editing by NGA removed many voids, in particular those caused by water, a great number of voids remain. Because many applications required continuous DEMs, several techniques have been developed for void filling which fall into two general categories: (i) replacement with elevation values from other data sources; and (ii) interpolation.

Several techniques have been developed to fill data voids by replacement with elevation values from other data including the 'fill and feather' approach (Dowding et al. 2004), the 'delta surface approach' (Grohman et al. 2006), and the triangulated irregular network-based delta surface approach (Luedeling et al. 2007). Algorithms differ primarily in how any bias between SRTM and other elevation data is accounted for to ensure a smooth transition at the void interfaces. The delta surface approach has emerged as the most versatile technique and is currently in use by NGA and its contractors.

Many different types of elevation data have been used to fill the voids in SRTM data, including GTOPO30 (Jarvis et al. 2004), Advanced Spaceborne Thermal Emission and Reflection Altimeter (ASTER) (Crippen et al. 2007; Kääb 2005), and contour lines from topographic maps (Luedeling et al. 2007).

Different interpolation techniques have been used to fill voids in SRTM data. In a comprehensive comparison of eight common techniques by Reuter et al. (2007), the choice of the best algorithm was found to depend both on the size and terrain type of the void. Kriging and inverse distance weighting are best for small- and medium-sized voids in relatively flat low-lying areas, spline is best for small- and medium-sized voids in high-altitude and dissected terrain, triangulated irregular network or inverse distance weighting is best for large voids in very flat areas, and an advanced spline method (ANUDEM) is best for larger voids in other terrain.

There is some disagreement as to whether replacement with other data or interpolation is the best approach to fill SRTM data voids. For small data voids, interpolation is a reasonable strategy, but this approach may not be suited for larger voids in mountainous areas. Crippen et al. (2007) found replacement with ASTER thermal imagery to be superior to interpolation in particular where voids cross ridges or canyons. Luedeling et al. (2007) found replacement with elevation data (40-m contours) from traditional topographic maps (1 : 200,000) to be the most suitable replacement for large data voids in mountainous areas. Reuter et al. (2007) found that the use of auxiliary information from lower resolution DEMs (SRTM30 and GTOPO30) did not improve the quality of the final elevation model relative to interpolation without auxiliary information, and that only higher-resolution DEMS should be used. It should also be noted that the two approaches to void filling are not necessarily mutually exclusive because the delta surface approach (Grohman et al. 2006), in fact, uses a combination of replacement to fill the void and interpolation to improve the overall surface at the void interfaces.

EFFECT OF LAND COVER

The SRTM did not produce a 'bare-earth' DEM. The elevation values represent the effective height determined by the complex vector sum of all the returned signals from within the pixel being imaged. Only for bare-ground areas do the SRTM data reflect the height of the actual ground surface. For vegetated areas, the return was influenced by the vegetation height, structure, and density. For very dense vegetation, little or no signal returned from the ground below. Clear cuts in dense forests are therefore readily noticed. This characteristic of SRTM elevation data can be utilized to derive vegetation heights by subtracting of a bare-earth

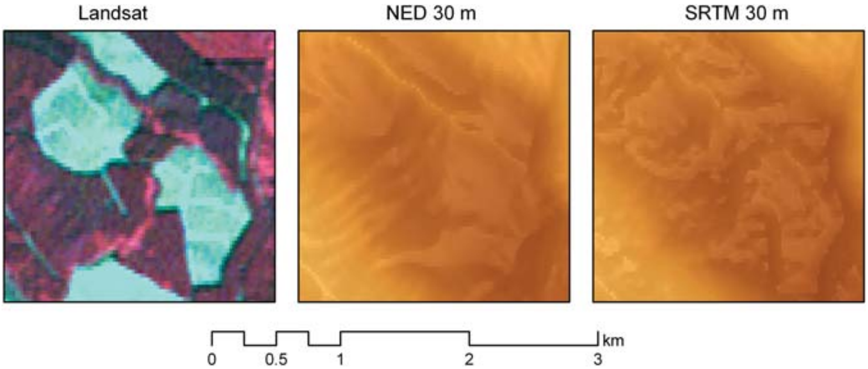

Fig. 9. Comparison of the 30-m NED and SRTM elevation data for a study site in Western Washington near Mount Rainer. Elevation data are shown as shaded relief images. Forest clear cuts are visible on the Landsat image and the boundaries appear as edges in the SRTM data. Such edges increase slope estimates and produce unreliable drainage characteristics.

DEM for other sources (e.g. Kellndorfer et al. 2004; Simard et al. 2006). However, the C radar often penetrated the vegetation canopy significantly (e.g. Carabajal and Harding 2006) and, therefore, the off-set between the SRTM elevation and a bare-earth DEM may underestimate the actual vegetation height. Corrections can be applied to account for this penetration, but require knowledge of the vegetation type and density (Hofton et al. 2006).

More than simply increasing height, forest cover often works to smooth the SRTM elevation data, hiding minor details. This is particularly the case in dense tropical forest in low-relief areas such as the Amazon Basin (Valeriano et al. 2006). Canopy height irregularities can also affect the determination of morphometric parameters of the terrain, and clear-cut borders can be misinterpreted as drainage channels (Valeriano et al. 2006). Figure 9 illustrates an example of the effects of forest canopy edges. Forest clear cuts are visible on the Landsat image and the boundaries appear as topographic SRTM data. Slope grids and drainage patterns are adversely affected as a result and not reliable at a fine scale.

Radar waves can also penetrate into frozen snow or ice, or very dry soil, potentially up to several meters. Depending on the state of the snow, the C-band-derived heights can be anywhere between the top of the snowpack and the buried ground surface. Areas of very dry sand cover may also have been penetrated by the C-band.

Large building, roads, towers, and bridges often result in shadowing, layover, and multipath artifacts in radar imaging. Given the 30 or 90 m posting of the final SRTM data, only the largest structures will be discernable. Figure 10 shows an example of such a large structure which is clearly visible. Even when individual structures are not visible, any urban SRTM pixel will be affected by the buildings within that pixel. As a result,

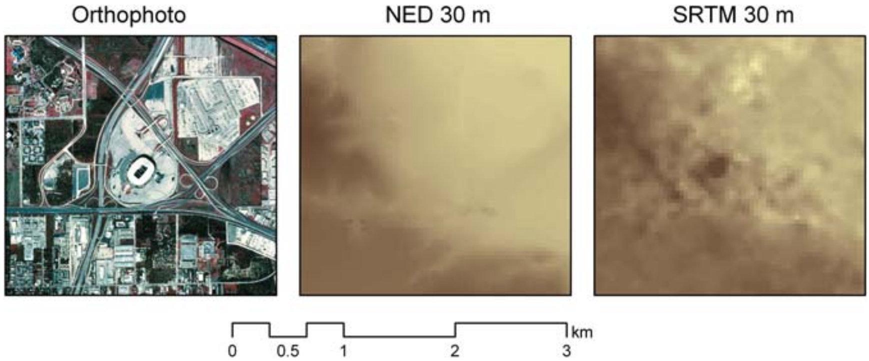

Fig. 10. Comparison of the 30-m NED and SRTM elevation data for Texas Stadium in Dallas, TX, USA. Elevation data are shown as shaded relief images. While the structure is clearly identifiable in the SRTM elevation model, the bare-earth NED elevation model does not reveal the structure.

heights in urban areas will typically be higher than bare ground, representing a bias toward overestimation of elevation.

Comparison to Other Elevation Data

Direct comparisons have been made between the SRTM elevation data and the NED in the United States because those data have traditionally been the most widely used. These comparisons suggest that the vertical accuracy of SRTM is considerably lower than the NED data with root mean square error (RMSE) values about three times higher (Shortidge 2006). SRTM elevation data also typically overestimate elevation relative to be bare-earth NED elevation data, in particular, in forested areas.

In a comprehensive comparison between the NED DEMs and 1 and 3 arc-second SRTM data for the continental United States, Guth (2006) determined that for basic parameters like average elevation and relief the two sets of data correlate very highly ($R^2 > 0.90$), but that for more complex terrain derivatives such as curvature and higher moments the correlations are much lower ($R^2 \approx 0.70$ or less). Overall, the information content of 1 arc-second SRTM data corresponds closer to that of 2 arc-second NED data, suggesting the effective resolution of SRTM is lower than the cell size of the data. In areas of low relief, the noise in SRTM data increases average slope, while in areas of high relief SRTM over smoothes topography and lowers average slopes (Guth 2006). Figure 11 shows a comparison of DEMs from various sources that illustrate some of these differences. The high-resolution light detection and ranging (LIDAR) DEM obviously shows a lot of detail not revealed at coarser resolutions. However, even after re-sampling to the same resolution, the SRTM data appear relatively 'noisy' compared to the LIDAR DEM as well as the

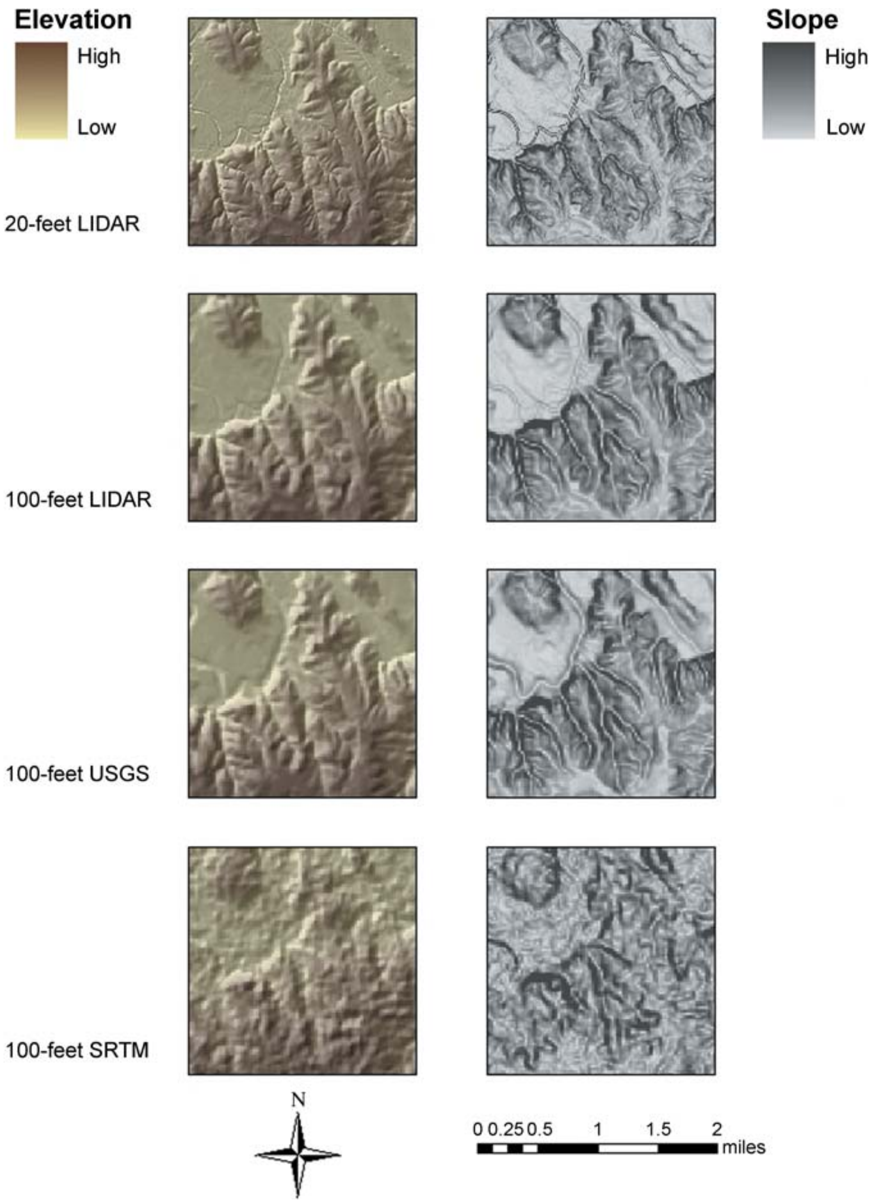

Fig. 11. Comparison of DEMs from various sources for a small study area in the North Carolina Piedmont. Elevation data are shown as shaded relief images. The original LIDAR DEM with a cell size of 20 feet obviously shows a lot of detail not revealed at coarser resolutions. However, even after re-sampling to the same resolution, the SRTM data appear relatively 'noisy' compared to the LIDAR DEM as well as the USGS DEM derived from traditional cartographic sources. As a result, slope estimates for low-relief areas in the SRTM are higher, while topography in steeper areas is smoother.

USGS DEM derived from traditional cartographic sources. As a result, slope estimates for low-relief areas in the SRTM are higher, while topography in steeper areas is smoother.

It should be noted, however, that NED data are derived from multiple sources of varying quality, and that the results of comparison with NED data may vary among specific locales. For example, in selected areas, high-resolution elevation data derived using LIDAR are increasingly replacing elevation data from traditional cartographic sources in the NED. For these areas, the NED at 1 arc-second resolution represents in fact LIDAR data coarsened from its original resolution.

Beyond comparing vertical accuracy, several studies have compared derivatives from SRTM data to those from other DEMs. Hancock et al. (2006) compared 3 arc-second SRTM data to higher-resolution DEMs for three catchments of different sizes and geomorphology in Australia. Results indicated that the SRTM data provided poor catchment representation. Hillslopes appeared as a linked set of facets with little of the complex curvature observed in high-resolution data. Catchment area, relief, and shape were also poorly captured by the SRTM data. Soil erosion modeling resulted in lower rates of erosion when using the SRTM data when compared to higher-resolution elevation data. Hancock et al. (2006) recommend that the SRTM data are of benefit for broad-scale qualitative assessments of large catchments, but that care must be used for quantitative assessment of catchment hydrology and geomorphology.

In an evaluation of SRTM data in the tropics, Jarvis et al. (2004) found SRTM to be a major improvement on the GTOPO30 data and of similar quality as traditional topographic maps at a scale of 1 : 25,000 or smaller. However, digitized 1 : 10,000 topographic maps, if available, are expected to produce better results, because many topographic features captured at that scale are not present in 3 arc-second SRTM data.

Researchers have also developed ways to combine SRTM and other elevation data in meaningful ways. Yun et al. (2005) merged SRTM data with a high-resolution InSAR DEM. While lower in resolution, the addition of the SRTM information improved the spatial coverage, reduced the artifacts, and filled data voids in the original InSAR DEM. Liao et al. (2007) also utilized SRTM data to improve the quality and consistency of an InSAR DEM obtained by the ERS-1 and ERS-2 satellites. In both these examples, the SRTM data are used to reduce the phase errors in the SAR-generated DEMs.

Geoscience Applications of SRTM Elevation Data

Since their release, SRTM datasets have found their way into many areas of research that require topographic data. The new SRTM DEMs have probably had the largest impact on studies of regions for which reliable, high-resolution digital topography was not previously available. Even for jurisdictions where higher-resolution DEMs are available, coarser-resolution SRTM data are being employed for hydrological modeling because it provides greater uniformity of quality and coverage that enables more reliable comparison across jurisdictional boundaries (e.g. Rödel and Hoffman 2005).

FOREST ECOLOGY

Determining forest density and structure using airborne LIDAR and radar has become a well-established technique. The availability of SRTM data has provided an opportunity to apply similar principles to much larger areas.

In general, it has been found that the SRTM elevation values in forested areas fall somewhere between the ground and the top of the canopy. Exactly, how far the signal penetrated into the canopy at a particular location is dependent on the interaction of the radar signal with the branches and leafs. The result is that when a bare-earth DEM is subtracted from a SRTM DEM, the difference produces an underestimate of forest height. Studies that have utilized SRTM data to determine forest height have therefore typically relied on calibration using field validation, airborne radar or LIDAR, or both. The objective of the calibration is to determine if a constant relationship can be derived between SRTM forest height and the actual forest height. If such a relationship was found for a particular type of forest, the calibration results can be used to estimate forest height for much larger areas. This approach has been applied to several different forest types (Heo et al. 2006; Hofton et al. 2006; Kellndorfer et al. 2004; Kenyi et al. 2006; Simard et al. 2006; Walker et al. 2004).

Figure 12 shows an example of the application of SRTM data to obtain forest height based on the work by Simard et al. (2006) in the Florida Everglades. The USGS DEM is a bare-earth DEM derived by the interpolation of a larger number of ground control points. The SRTM elevation values are clearly much higher and reflect the mangrove cover in this area. Simard et al. (2006) used the difference between the bare-earth DEM and the SRTM DEM to estimate mangrove forest height after calibration using airborne LIDAR.

One obvious concern in the utilization of SRTM data is whether the vertical accuracy of SRTM (approximately 9 m at the 90th percentile) is sufficient for a detailed assessment of forest height in the range of tens of meters. Error mitigation strategies are therefore considered necessary to obtain reliable estimates of forest. Kellndorfer et al. (2004) utilized outlier removal and averaging of the SRTM data to improve forest height estimates. Walker et al. (2007a,b) employed a knowledge-based approach to sample averaging, which effectively reduced phase-noise error and allowed for reliable forest height determination for study sites in the Midwestern United States.

Further advances in this area have been made possible by the Geoscience Laser Altimeter System (GLAS) on the ICESat, the first spaceborne LIDAR

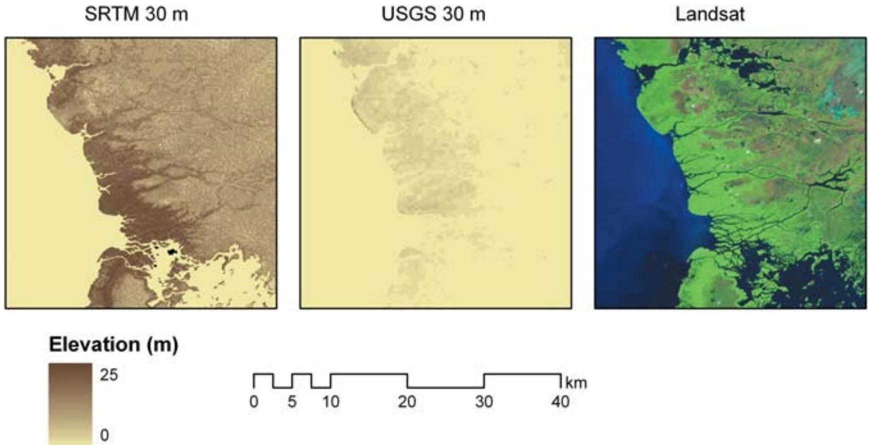

Fig. 12. Comparison of SRTM and USGS DEM for the southwestern portion of the Florida Everglades. The USGS DEM is a bare-earth DEM derived by the interpolation of a large number of ground control points. The SRTM elevation values are clearly much higher and reflect the mangrove forest in this area. Subtracting the bare-earth DEM from the SRTM DEM provides an initial estimate of mangrove height, but requires adjustment for vertical bias, as well as calibration with field surveys or airborne LIDAR.

instrument for continuous global coverage. Combining GLAS and SRTM data, in combination with airborne LIDAR data for calibration, has been successfully applied to characterize forest structure (Carabajal and Harding 2006; Sun et al. 2008).

GLACIOLOGY

The SRTM has become widely used in glaciology to estimate glacier mass balance. While SRTM only provides a single snap shot of elevation for February 2000, the accuracy of SRTM is deemed sufficient to provide contemporary observations of larger glaciers with satisfactory accuracy and coverage (Bamber and Rivera 2007). Because mass balance estimates of glaciers are most meaningful when a reliable time-series is available, SRTM data are often combined with topographic data from other sources. Berthier et al. (2007) compared SRTM data to a DEM for 2004 derived from SPOT5 to characterize glacier mass balances in the Western Himalayas. Biases in the two DEMs were determined by examining stable areas around the glaciers where no elevation change is expected, and these biases were modeled and removed to permit unbiased comparison of the two DEMs from different sources. Surazakov and Aizen (2006) and Aizen et al. (2007) combined historical geodetic surveys, aerial photographs, and topographic maps with SRTM and ASTER data to document the retreat of the Tien Shan glacier over the past 100 years. Racoviteanu et al. (2007) compared DEMs from historic topographic maps with SRTM and ASTER data to characterize the Nevado Corupuna glacier in the Peruvian Andes. Kääb (2005) combined SRTM and ASTER data to estimate glacier flow velocities in the Bhutan Himalaya, revealing a large difference in velocities between northern and southern glacier tongues. Keller et al. (2007) found good agreement between airborne laser altimetry and SRTM data for the Tyndall glacier in southern Chile. Combined, these studies suggest that SRTM has become widely used in understanding glacier dynamics, including glacier response to climate change.

VOLCANOLOGY

Determining lava flows from volcanoes is necessary to estimate eruption volumes and to model volcano eruption behavior. Similar to estimating mass balances of glaciers, a time series of elevation data is needed to characterize lava flows, and SRTM data have been useful in this regard. Thickness and extent of recent lava flows were determined by comparing historic DEMs and SRTM data for the Westdahl Volcano in Alaska (Lu et al. 2004). Results agreed reasonably well with field observations.

As with many applications, 3 arc-second version of the SRTM data made available for areas outside the United States is considered a limitation considering that 1 arc-second data were collected. The potential loss of information can be quantified by comparing the results of 1 and 3 arc-second SRTM data for sites within the United States. In an assessment of volcano morphology, Wright et al. (2006) determined that the re-sampling obviously resulted in a loss of information, but that the general morphological shape of volcanic edifices was preserved. This suggests that SRTM data are very appropriate for volcanic hazard assessment. Figure 13 shows an example of the morphology of Mount Etna on Sicily, Italy.

The SRTM data have also been successfully applied to the modeling of lahar hazards, in particular, when the SRTM data are supplemented with ASTER DEMs (Hubbard et al. 2007; Huggel et al. 2008).

GEOMORPHOLOGY

The SRTM data have also become a widely used data source to characterize unique landforms in remote regions which previously lacked sufficiently reliable topographic information. Bailey et al. (2007) found SRTM data sufficient to identify fluvial and eolian features on large ignimbrite sheets in Chile but insufficient in vertical accuracy to document the height or depth of features to characterize degrees of erosion. Reimold et al. (2006) employed SRTM data to characterize a possible impact structure at Serra da Cangalha in Brazil. Blumberg (2006) utilized SRTM data to characterize dunes in arid regions of the world. SRTM data were sufficient to characterize large dunes which tend to be complex and compound but insufficient to identify smaller dunes. The X-band data were found to be more sensitive

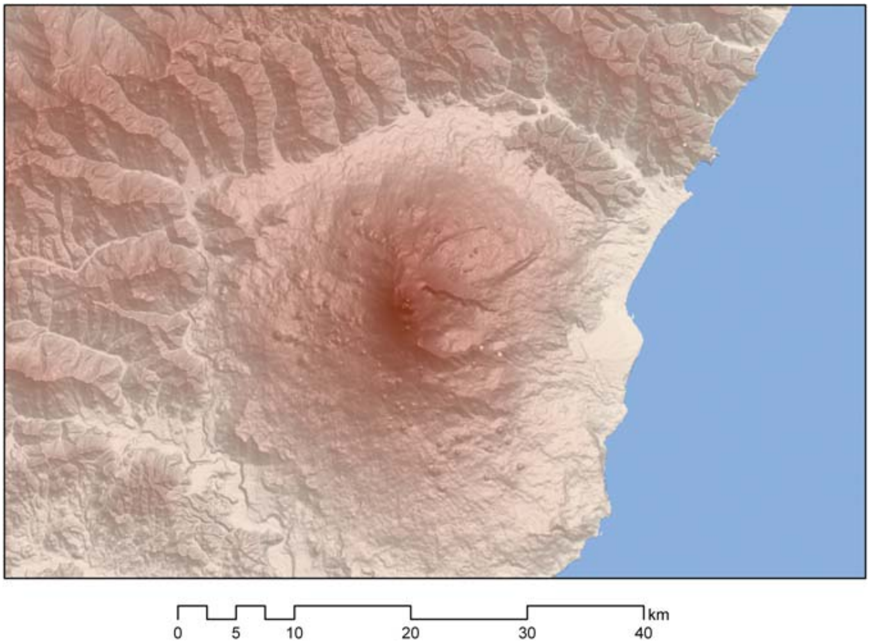

Fig. 13. Hillshaded elevation model of Mount Etna on Sicily, Italy. The 3 arc-second SRTM data have proven reliable for general morphological characterization of volcanoes worldwide.

to the smaller-scale undulations on the compound dunes and better revealed the full height of the dunes. Figure 14 shows an example of the unique patterns identified in large dunes in the Western Sahara. Grohman et al. (2007) employed SRTM data for a morphotectonic analysis of the Poços de Caldas Alkaline Massif in Brazil with results in good agreement with those derived from 1 : 50,000 topographic maps. SRTM data were also a key element in an analysis of the Holocene evolution of the Aral Sea (Reinhardt et al. 2008). SRTM data provided a consistency in the quality of the elevation model not previously available for a study area covering multiple jurisdictions. Ghoneim and El-Baz (2007) employed SRTM data to characterize ancient drainage networks in the Eastern Sahara, suggesting its usefulness in reconstructing paleohydrology in desert regions. Luedeling and Buerkert (2008) combined Landsat images, SRTM data, and geological survey data to characterize desert oases.

The SRTM data have also proven useful for landform characterization in densely vegetated areas. In many tropical rain forest regions in particular, details of the terrain are mostly blurred in traditional remote sensing images, and topographic data are often lacking. While the digital topographic from SRTM closely corresponds to the mean height of the vegetation in densely forested areas, at a regional scale the DEM follows the terrain features below the vegetation. Almeida-Filho and Miranda (2007) demonstrate that

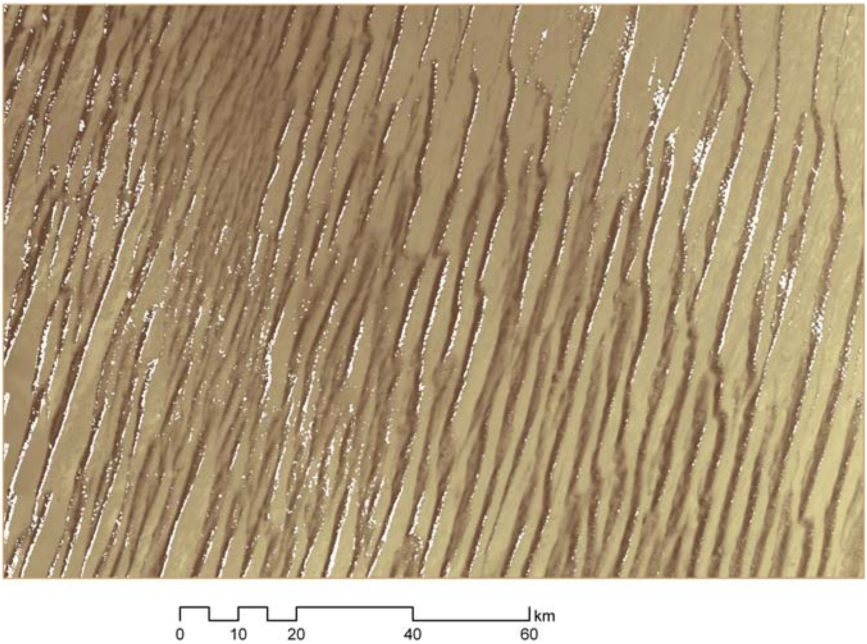

Fig. 14. Hillshaded elevation model of dune structures in the Sahara in Western Algeria. Data voids (shown in white) appear along the ridges of the dunes. SRTM has provided unprecedented opportunities to characterize unique landforms on a global scale.

for a study region in Central Amazonia terrain features were poorly defined in Japan Earth Resources-1 and Landsat Thematic Mapper imagery, but could effectively be characterized using SRTM. Analysis revealed the relics of a large ancient drainage system hidden by the tropical rain forest, which has provided new insights into the formation of the Amazonian basin. Hamilton et al. (2007) have also demonstrated how SRTM can be used to characterize the complex floodplain geomorphology in tropical river systems.

One of the principal applications of DEMs is the modeling of runoff processes. The availability of SRTM has made it possible to accomplish this at an unprecedented scale, but the model results require validation with higher-resolution data. A hillslope sediment delivery model based on SRTM was calibrated using observed sediment yield data and validated using higher-resolution DEMs by Verstraeten (2006). While overall results were in good agreement, steeper topography is smoothed in the SRTM data, reducing the average erosion rate, while in flatter downslope areas larger slope values are found in the SRTM data, increasing the transport potential. Results suggest careful calibration at each spatial resolution is needed to obtain reliable results. Walcott and Summerfield (2008) employed SRTM data to explore the scale dependence of geomorphological properties of drainage basins in Southeast Africa. Such analyses over large regions have traditionally been limited to selected counties but are now possible for any region.

HYDROLOGY

Topographic data are widely used to determine hydrological properties of a landscape, including the extraction of drainage networks and upstream catchment areas. Combined with information on slopes, additional parameters such as wetness index and stream power can also be derived. The availability of SRTM DEMs now permits rapid, global assessment of catchment areas, channel slopes, estimates of discharge, spatial variations in stream power, and erosion rates.

The DEMs are widely used to model rainfall-runoff processes. SRTM data have generally been found to be of sufficient accuracy for hydrological model applications. Compared to higher reference DEMs, Ludwig and Schneider (2006) found that SRTM data lead to slightly modified runoff patterns and to marginally increased flood peaks under wet watershed conditions. Prediction of hydrological parameters, such as the topographic wetness index, was found to be least reliable in areas of high relief.

The near-global coverage is one of SRTM truly unique characteristics, and assessments previously only conducted on regional scale can now be accomplished at global scales. One such application is the HydroSHEDS project (http://hydrosheds.cr.usgs.gov/). HydroSHEDS provides hydrographic information for regional- and global-scale applications in a consistent format at various scales, including river networks, watershed boundaries, drainage directions, and flow accumulations. Figure 15 provides an example illustration of the typical data provided. HydroSHEDS is derived from 3 arc-second SRTM data resolution. The original data have been hydrologically conditioned using a sequence of automated procedures, including void-filling, filtering, stream burning, and upscaling techniques. Preliminary quality assessments indicate that the accuracy of HydroSHEDS significantly exceeds that of existing global watershed and river maps. HydroSHEDS has been developed by the Conservation Science Program of World Wildlife Fund, in partnership with the USGS and several other agencies. It represents a truly global assessment that was not previously possible.

While the creation of broad-scale hydrographic data from SRTM has been successful, finer-scale applications have shown some of the limitations of SRTM. For a low-relief drainage basin, 3 arc-second SRTM elevation model performed poorly in correctly characterizing drainage features for a small low-relief watershed in the Amazon Basin (Valeriano et al. 2006), largely resulting from the effects of forest canopy.

Another area of hydrological applications of SRTM is the determination of surface water height. Changes in surface water storage and discharge are poorly known globally. SRTM has provided global measurements of both surface water area and elevation. To properly estimate surface water

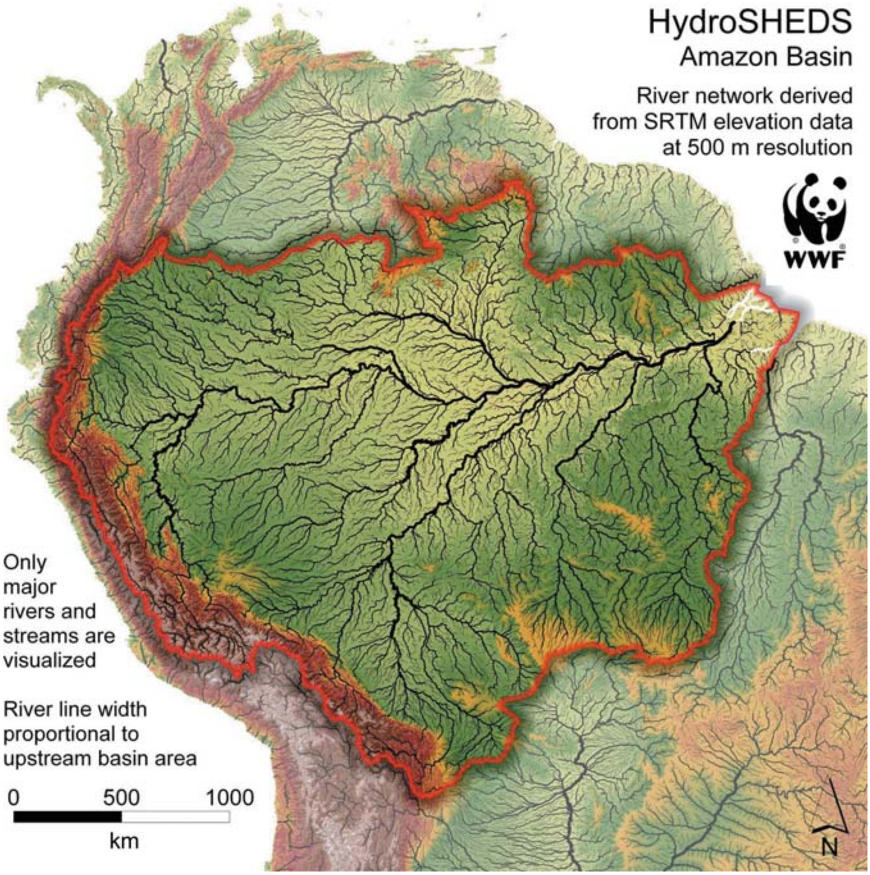

Fig. 15. Sample data of the global HydroSHEDS database. HydroSHEDS is one of the first applications to demonstrate the potential of having near-global elevation data available. Image courtesy of WWF.

storage and discharge, however, reliable estimates of the changes in surface water height are needed. Radar pulse returns from water surfaces are a function of roughening by wind or wave action. For a given roughness, shorter radar wavelengths produce greater backscatter than longer wavelengths. Because X-band wavelengths are slightly shorter than C-band, surface water height estimates are more widely available from the X-band than from the C-band. While available in many areas, the surface water height estimates from SRTM have been found to be much less accurate compared to the surrounding terrestrial areas (Alsdorf and Lettenmaier 2003; Alsdorf et al. 2007a). Because of the degraded height accuracy, water slopes calculated from SRTM require long reach lengths to decrease the influence of noise. For example, Hendricks and Alsdorf (2004) and LeFavour and Alsdorf (2005) derived surface water height estimates along most of the Amazon

River. The resulting water slope compared well to ground reference data and discharge estimates at three locations were within 10% of the observed flow. Water elevations and discharge were obtained from *in situ* gages at several stations and averaged over the 10-day acquisition period in February 2000.

The application of spaceborne radar altimetry measurements to surface water height remains of great interest (Alsdorf et al. 2007a,b; Birkett et al. 2002; Kiel et al. 2006). As a result of the experience with SRTM and ground-based radar altimetry, an effort is currently underway to implement a new space-based radar altimetry instrument. The Water and Terrestrial Elevation Recovery Hydrosphere Mapper mission (WATER HM) proposes a Ka-band Radar INterferometer (KaRIN; 0.86 cm wavelength) (http://bprc.osu.edu/water/). KaRIN is essentially a smaller version of SRTM with two Ka-band SAR antennae at opposite ends of a 10-m boom and both antennae transmitting and receiving the emitted radar pulses along both sides of the orbital track. Look angles are limited to 4.5° providing a 120-km wide swath. Interferometric SAR processing of the returned pulses yields a 5-m azimuth and 10–70 m range resolution, with elevation accuracy of ±50 cm.

FLOODING

The possibility of global sea-level rise due to climate change has prompted great interest in modeling coastal flooding. Because SRTM data are the most accurate elevation data for many regions of the world, it is increasingly being used for coastal flood risk assessment (Demirkesen et al. 2007). In a comparison of DEMs of varying quality and resolution, Sanders (2007) found SRTM data to be quite reliable as a source of elevation data for flood inundation modeling. While not surprisingly high-resolution LIDAR data were found to be the best source, 1 arc-second SRTM data compared well to other moderate-resolution airborne InSAR and NED DEMs. Speckle noise was identified as a major limitation of the SRTM data for flood inundation modeling because the noise results in undulations in otherwise flat areas, producing a flood zone that appears as a network of pools. Schurmann et al. (2008) also found that flood inundation analysis using SRTM compared well to other higher-resolution DEMs, and that SRTM data are a valuable source for flood information, in particular, in relatively large and homogenous floodplains.

OTHER APPLICATIONS

Several other applications of SRTM data have emerged in recent years, including the analysis of ground moving objects (Suchandt et al. 2006), the development of groundwater flow models (Fredrick et al. 2007), the identification of possible archaeological sites (Menze et al. 2006), and ocean and river current measurements (Romeiser et al. 2005, 2007). Many of these applications have only recently been published, and it seems likely that other novel examples of the use of SRTM data will emerge.

Summary of Strengths and Weaknesses

The SRTM data have become an invaluable source of topographic information for researchers in many fields. Data quality characteristics have been well documented, including its vertical accuracy, the presence of data voids, the effect of speckle noise, and the influence of vegetative cover. Several solutions to address the limitations of SRTM data have also been developed.

The key strength of the SRTM data lies in its near-global coverage at a consistent quality, providing unprecedented opportunities for regional and global applications. The quality of the SRTM data has gradually improved as a result of substantial editing, the development of void filling procedures, and the refinement of techniques to extract the most amount of useful information from the SRTM C- and X-band data.

One limitation of the SRTM data lies in its spatial resolution: 1 arc-second data available for the United States have an effective resolution in terms of information content of approximately 2 arc seconds, while 3 arc seconds are at present the best available for the rest of the world. These resolutions represent serious limitations for fine-scale analysis and have been well documented. A second limitation lies in the vertical accuracy of the SRTM data: 9 m or better absolute vertical accuracy based on the 90th percentile of the error distribution. This vertical accuracy is much less than can be achieved using other methods for smaller study areas and limits the ability to detect relatively small topographic features. A third limitation lies in the fact that SRTM data represent 'first-return' elevation data, resulting in substantial overestimates of elevation in vegetated areas. A fourth limitation lies in the presence of speckle noise, which for some applications needs to be reduced for results to be reliable. One final caution for researchers is the fact that multiple versions of the SRTM data are currently available, and users are cautioned to review the data processing techniques applied in terms of data editing, void filling, and other enhancements before obtaining and using the data.

The SRTM has exceeded its original objectives and has clearly demonstrated the potential of satellite radar altimetry. Complementary laser altimetry systems are already in operation, and future endeavors, such as the Terra SAR-X mission and the proposed WATER HM mission, will build on the experience gained with SRTM.

Short Biography

Paul Zandbergen is an Associate Professor in the Department of Geography at the University of New Mexico, New Mexico, USA. He obtained his PhD in Resource Management and Environmental Studies at the University of British Columbia in Vancouver, Canada. He previously held positions as Assistant Professor at York University in Toronto, Canada, and the University of South Florida in Tampa, Florida, USA. He is a geographic information scientist with interests in both the fundamentals of geographic information science as well as the applications of geospatial technologies to several fields, including water resources, spatial ecology, environmental health, and criminal justice. His current research has focused on issues of scale, error, and uncertainty in spatial analysis, as well as on the robustness of spatial analytical techniques. In recent years, he has published in journals with an emphasis on geographic information science (including *Applied GIS*, *Computers, Environment and Urban Systems*, *International Journal of Health Geographics*, and *Transactions in GIS*) as well as in journals with specific geographic information science applications (including *Environmental Health Perspectives*, *Journal of Epidemiology and Community Health*, and *Justice Research and Policy*).

Note

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