Accuracy and resolution of shuttle radar topography mission data

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[1] We assess the accuracy and resolution of topography data provided by the Shuttle Radar Topography Mission (SRTM) through spectral comparisons with the National Elevation Dataset (NED) and a high-resolution laser data set of the 1999 Hector Mine earthquake rupture. We find that SRTM and the NED are coherent for wavelengths greater than 200 m, however the spatial resolution of the NED data is superior to the SRTM data for wavelengths shorter than 350 m, likely due to the application of a boxcar filter applied during final SRTM processing stages. From these results, a low-pass filter/decimation algorithm can be designed in order to expedite large-area SRTM applications. *INDEX TERMS:* 1243 Geodesy and Gravity: Space geodetic surveys; 1294 Geodesy and Gravity: Instruments and techniques; 6969 Radio Science: Remote sensing; 6924 Radio Science: Interferometry; 8199 Tectonophysics: General or miscellaneous. **Citation:** Smith, B., and D. Sandwell, Accuracy and resolution of shuttle radar topography mission data, *Geophys. Res. Lett.*, *30*(9), 1467, doi:10.1029/2002GL016643, 2003.

1. Introduction

[2] The Shuttle Radar Topography Mission (SRTM) [*Farr and Kobrick*, 2001] collected radar interferometry data over 80% of Earth's landmass from 60°N to 56°S latitude in February of 2000. C-band (λ = 5.6 cm) data acquired during the mission, currently being processed by the Jet Propulsion Laboratory (JPL), is expected to have horizontal and vertical accuracy near 20 m and 16 m (linear error at 90% confidence), respectively, for the final 1 arc-second data release of the U.S. [*Jordan et al.*, 1996; *Slater et al.*, 2001]. While 1 arc-second data (30 m, SRTM-1) will only be available for locations within the U.S., under the NASA-NIMA Memorandum of Understanding for SRTM, data outside of the U.S. will eventually become publicly available at 3 arc-second sampling (90 m, SRTM-3) [*M. Kobrick*, personal communication, 2002].

[3] Once complete, the SRTM data set will provide a new level of global topographic information critical for a number of scientific investigations, specifically in areas outside of the U.S. where the quality of data is typically poorer [*Berry et al.*, 2000]. Prior to the scientific applications of SRTM data, however, it is necessary to understand the vertical precision/accuracy and horizontal resolution of the data set. In the case of SRTM, the vertical precision of the data depends on the inherent phase noise in the SRTM radar, while the horizontal resolution depends on the signal-to-noise ratio as a function of horizontal wavelength. While the vertical accuracy of the final topography data can be determined using GPS control points, the relative vertical precision and horizontal resolution of the data can only be established by performing a cross-spectral analysis between SRTM data and another large-area "ground-truth" data set. Here we assess the quality of SRTM data through comparisons with two other data sets in the Mojave Desert area of Southern California. We examine the power and coherence of SRTM, the National Elevation Dataset (NED), and the Hector Mine Airborne Laser Swath Mapping (ALSM) data set in order to establish the horizontal resolution of C-band 30 m SRTM topography.

2. Data Characteristics

2.1. SRTM Data

[4] Both ascending and descending C-band swaths from the Shuttle interferometer were processed into a digital elevation model (DEM) by the Jet Propulsion Laboratory [*Hensley et al.*, 2000]. Each data posting of the final DEM represents a height in meters above the WGS84 ellipsoid (PI Processor) or the WGS84 geoid (Production Processor) in the WGS84 latitude/longitude co-ordinate system [*NIMA*, 1994; *SRTM_Topo*, 2001]. For this study, both PI and Production Processor versions of SRTM were analyzed; no significant differences (other than the geoid/ellipsoid reference and minor data voids) were identified in accuracy or resolution, and so the results discussed in this paper were chosen to reflect that of the PI Processor DEM. Data points within the C-band SRTM-1 grid are horizontally spaced at 1 arc-second intervals, or ~30 m intervals at the equator.

2.2. NED Data

[5] The National Elevation Dataset (NED), assembled by the U.S. Geological Survey, is a compilation of many data sources (7.5 minute, 15-minute, 2 arc-second, and 3 arc-second DEMs extending as far back as 1978) of varying horizontal datum, map projections, and elevation units. The final raster NED product reflects elevation values that have been converted to consistent units, recast into a geographic projection, and referenced to the NAD83 horizontal datum [*Gesch et al.*, 2002]. Like the SRTM-1 data set, the NED DEM has approximately 30 m horizontal postings and is available for regions within the United States.

2.3. Hector Mine ALSM Data

[6] The Hector Mine Airborne Laser Swath Mapping (ALSM) data set was acquired along the rupture zone of the M = 7.2, 1999 Hector Mine earthquake [*Hudnut et al.*, 2002]. On April 19th, 2000, a field team from the U.S. Geological Survey acquired the entire high-resolution topography data set using a helicopter-based laser instrument platform. The helicopter flight lines traversed the rupture zone along most of its length (~50 km), acquiring multiple swath widths of, on average, 150 m. The laser beam

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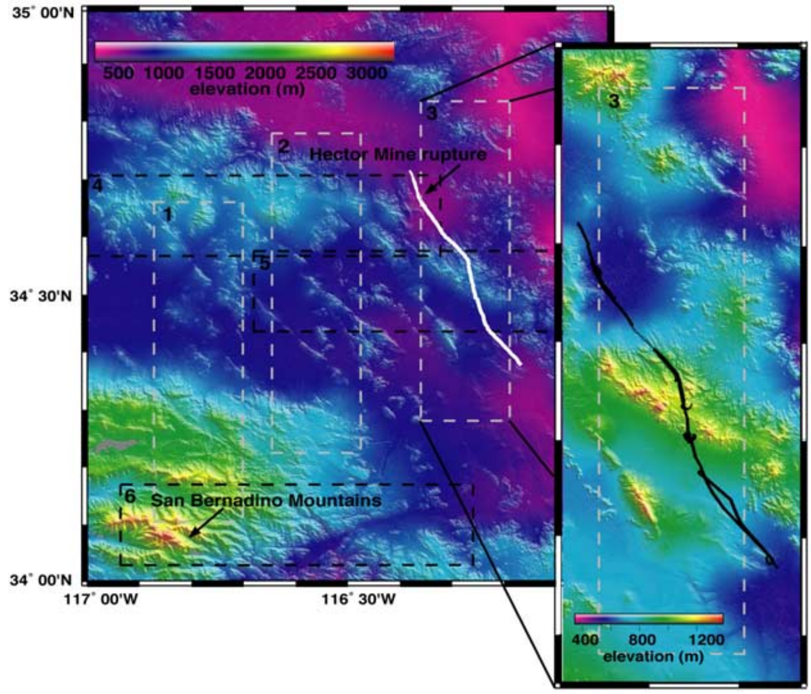

Figure 1. Location map of the N34W117 DEM of the SRTM data set. White dashed boxes depict examples of column (latitude) cross-spectral estimates performed on the SRTM and NED DEMs. Similarly, black dashed boxes depict row (longitude) estimates. Associated numbers in upper left corners of boxes correspond to the six cross-spectral analyses as noted in the Table 1. Outset shows a close-up view of the Hector Mine ALSM tracks (black) used in this study.

scanned continuously, rotating through nadir angles of +/− 18° while flying along the fault scarp. The processed Hector Mine ALSM survey data have been geodetically referenced to the WGS84 ellipsoid using onboard GPS, and have horizontal postings spaced ~25 cm.

3. Data Preparation

[7] In order to assess the accuracy and resolution of the 30 m C-band SRTM DEM, cross-spectral analyses were performed between pairs of the above data sets in an area of Southern California near the location of the 1999 Hector Mine earthquake (Figure 1). Prior to these comparisons, the data were projected into a common latitude, longitude, and height system. The Hector Mine ALSM topography data required a tedious re-sampling scheme in order to make the data more compatible to that of SRTM and the NED. In doing so, we resampled the Hector Mine ALSM data as a function of nadir angle from −18.0° to −2.3° and +2.3° to +18.0°. We also constrained along-track spacing of data points to a minimum of 8 m (Figure 1, outset).

[8] Six sub-regions of the N34W117 SRTM DEM were chosen for cross-comparison with the NED: three regions in the longitudinal direction (row analyses) and three in the latitudinal direction (column analyses). These specific analyses spanned regions of both high and low relief of the Hector Mine area grid (Figure 1). Each cross-spectral analysis contained 600 profiles of 2048 samples. A Hanning-tapered window of length 2048 was applied to each profile segment. Spectral estimates from the 600 independent profile segments were then ensemble averaged to form both cross-spectral and coherence estimates.

[9] Following the resampling algorithm discussed above, a maximum possible number of profiles were also extracted from the Hector Mine ALSM data and segmented into 402 independent profiles (Figure 1, outset). These subparallel profiles, each containing 512 samples, were also extracted from both NED and SRTM resampled grids for cross-comparison. Spectral estimates from the 402 independent profile segments were ensemble averaged to form both cross-spectral and coherence estimates. Because of the fewer, relatively shorter profiles available for cross-comparison, cross-spectral estimates of Hector Mine ALSM data are less reliable than those of the SRTM-NED comparison.

4. Cross-Spectral Analyses Results

[10] Using either multiple rows/multiple columns or multiple profiles along the helicopter flight track, three different cross-spectral analyses were performed in one dimension following the *Welch* [1967] method for estimates of both power and coherence. The coherence, γ_{xy}^2, is a measure of correlation between any combination of two signals (SRTM, NED, or Hector Mine ALSM). A high coherence (close to 1) indicates the signal to noise ratio (SNR) of both data sets is high, while a low coherence indicates one or both of the data sets has a low SNR. When both data sets have similar SNR characteristics (initially hypothesized as that of SRTM and NED), a coherence of 0.25 indicates the longest wavelength at which both have a

SNR of 1 and provides a good estimate of the resolution of the data sets [*Bendat and Piersol*, 1986]. Alternatively, if one data set has a much higher SNR than the other (such as Hector Mine ALSM data), a coherence of 0.5 identifies the spectral region at which the SNR of the inferior data set is 1. The degree of reliability for such spectral estimates of coherence depends significantly on the length of each profile and number of independent profiles available for the ensemble average.

4.1. SRTM vs. NED

[11] First we inspect the results of the SRTM and NED cross-comparison. The coherence estimate between both data as a function of wavelength is shown in Figure 2a, where the grey curve corresponds to a representative column analysis (box 3, Figure 1), while the black curve corresponds to a representative row analysis (box 5, Figure 1). The remaining four analyses displayed similar coherence versus wavelength results (Table 1). Initially, we assume that the SRTM and NED data have similar signal and noise spectra and that a 0.25 coherence indicates the full wavelength (156 m) where their associated SNRs are 1. We next suppose that either the NED or SRTM data has high SNR at wavelengths near 156 m. In this case, a 0.5 coherence indicates the full wavelength (210 m) where the inferior data set has a SNR of 1. But which data set has the higher SNR in the 150 to 200 m wavelength band - NED or SRTM? In order to answer this question, the superior accuracy of the Hector Mine ALSM topography is required for cross-comparison with both SRTM and NED.

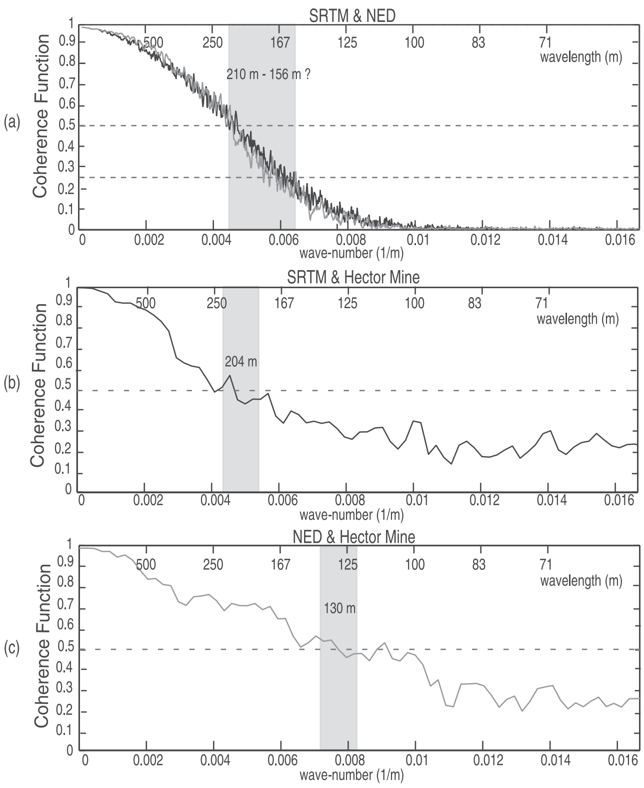

Figure 2. Coherence as a function of wavelength. (a) SRTM vs. NED coherence. Grey and black lines represent boxes 3 and 5 (Figure 1), respectively. (b) SRTM vs. Hector Mine ALSM coherence. (c) NED vs. Hector Mine ALSM coherence.

Table 1. Wavelength Estimates of SRTM-NED Cross-Comparisons at 0.25 and 0.5 Coherence[a]

	rms difference	$\gamma^2_{xy} = 0.25$	$\gamma^2_{xy} = 0.5$
Box 1	5.72 m	152 m	195 m
Box 2	3.87 m	163 m	218 m
Box 3	4.75 m	156 m	204 m
Box 4	4.81 m	159 m	198 m
Box 5	4.90 m	161 m	211 m
Box 6	6.29 m	141 m	175 m

[a]Boxed analyses correspond to the black and white dashed boxes of Figure 1. Calculated rms differences (SRTM-NED) are also listed. Coherence and corresponding wavelengths are listed for each box.

4.2. SRTM & NED vs. Hector Mine ALSM

[12] Next we assess the accuracy and resolution of both the SRTM and NED data by comparing each to the higher quality Hector Mine ALSM data. The rms difference between SRTM and Hector Mine ALSM data is 2.70 m, while the rms difference between the NED and Hector Mine ALSM data is significantly higher (3.50 m). Thus the SRTM data are considerably more accurate than the NED data. The coherence analysis, however, reveals that the NED data have better short wavelength resolution. For the SRTM-Hector Mine ALSM comparison (Figure 2b), the coherence falls below 0.5 at a full wavelength of 204 m. Additionally, we note the significant drop in coherence at wavelengths between 500 and 180 m in the SRTM data, to be discussed below. For the NED-Hector Mine ALSM comparison (Figure 2c), the coherence falls to 0.5 at a full wavelength of 130 m. Thus, the NED has higher accuracy than the SRTM data at shorter wavelengths. However, the NED-Hector Mine ALSM coherence is only 0.82 at a wavelength of 500 m while the SRTM-Hector Mine ALSM coherence is higher (0.90). In fact, from Figures 2b and 2c, we note that the NED data are inferior to the SRTM data for wavelengths longer than ~350 m. The overall higher accuracy of the SRTM data is explained by the fact that the spectrum of topography is red, and thus the rms difference is influenced more by the coherence at longer wavelengths.

[13] Is there a logical reason why the SRTM data has worse short wavelength accuracy than the NED? We believe that such behavior is due to a boxcar filter applied in the final stage of SRTM processing in order to reduce the short-wavelength noise. We illustrate this thought by comparing the ratio of the power in the SRTM (and NED) data to the power in the Hector Mine ALSM data (Figure 3). Because we regard the Hector Mine ALSM power spectrum as precise, a ratio of less than one reflects a loss in power in SRTM (or the NED) due to filtering or smoothing of grids. From Figure 3, we note that for wavelengths shorter than 1250 m, the NED to ALSM ratio (grey) is consistently higher than the SRTM to ALSM ratio (black), reflecting a loss of power in the SRTM data. This observation was confirmed by *S. Hensley* [personal communication, 2002]; the SRTM DEM was smoothed during final processing with a boxcar filter of widths varying between 5 and 9 pixels, depending on terrain roughness. To illustrate the effect of such a filtering scheme, we compare the power of a 6-pixel boxcar/sinc-function filter in Figure 3 (black dashed curve)

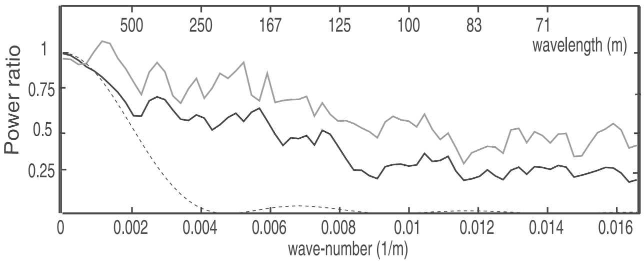

Figure 3. Power ratio of SRTM and NED signals to Hector Mine ALSM signal. Black line represents SRTM/Hector Mine ALSM power. Grey line represents NED/Hector Mine ALSM power. Black dashed line represents 6-pixel boxcar filter response in the wave-number domain.

to the SRTM to ALSM power ratio (black). The two curves show similar power loss in the 500–1000 m band. For example, at 500 m the boxcar filter attenuates the SRTM amplitude by $\sqrt{0.5}$, or approximately 0.707. As an aside, we note that the NED to Hector Mine ALSM power ratio exceeds 1 near a wavelength of 900 m, perhaps reflecting the higher noise level of the NED data in this band.

4.3. Phase Shift

[14] Large area SRTM and NED comparisons show a typical rms difference of 5.70 m and display signatures associated with a relative systematic shift of one of the grids towards the northeast direction. For these areas, we calculate an average phase shift of 0.467 pixels in longitude (11.87 m) and 0.343 pixels in latitude (10.58 m) between SRTM and the NED. Again, we use the Hector Mine ALSM data to determine which data set is improperly shifted by computing coherence after shifting each data set in a variety of directions. For the NED, a shift of 11.87 m east and 10.58 m north results in the best coherence between the NED and Hector Mine ALSM spectrum. Shifting the SRTM data in all directions repeatedly produced lower coherence. Thus, we suspect that the NED contains the geo-location error. It is likely that this identified shift is a result of the inherent geo-location accuracy of the NED source data (12.2 m, circular error at 90% confidence) [*USGS*, 1999].

4.4. SRTM Filter and Decimation

[15] As a final note, now that horizontal resolution has been established, a 2-D low-pass filter can be designed for a particular application, depending on whether a high resolution-high noise, or low resolution-low noise DEM is ideal. The cutoff wavelength of this filter should be selected to retain some of the low SNR data because additional filters can be applied at a later time, if necessary. Based on this resolution analysis of SRTM data, we find that there is almost no significant power at wavelengths shorter than ~180 m (Figure 2b), which also corresponds to the first zero crossing of the sinc-function filter (Figure 3) applied to the data. Therefore, with no additional filtering, it would be safe to decimate the data from a 30 m sampling to perhaps a 60 m sampling without losing information. Alternatively, if the data are decimated from 30 m sampling to 90 m sampling to meet the security constraints imposed by NIMA, a low-pass filter should be designed with small sidelobes in order to ensure that wavelengths above 180 m will not be aliased back into the longer wavelength part of the spectrum. The 90 m SRTM DEM that will eventually be made available for the entire globe will likely capture almost all of the information in the SRTM data.

[16] **Acknowledgments.** We thank NASA and JPL for providing the SRTM data set and Ken Hudnut and the U.S.G.S for providing the Hector Mine ALSM data set. We also thank the Associate Editor and two anonymous reviewers for their comments and rapid reviews. Bruce Bills provided a careful in-house review as well. This research was supported by the NASA Solid Earth and Natural Hazards program (NAGS-9623) and the NSF Earth Science Program (EAR-0105896).

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