

Improvements to ASTER elevation models for applications in Glaciology

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ABSTRACT

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Uses stereo imaging to produce Digital Elevation Models (DEMs) that can be used for numerous applications in Glaciology. However, artificial roughness present in ASTER DEMs can impede topographic analysis due to poor signal to noise ratios. In this study we post-process ASTER elevation data using a mesh denoising-algorithm, designed to reduce surface noise, over White Glacier on Axel HeiberG Island, NU, Canada. WE report the level of correction and associated errors of the method, then discuss the impact of using the corrected elevation models in hydrological analysis.

Keywords: Remote Sensing; Digital Elevation Models; Raster Processing; Glaciology

1. INTRODUCTION

Reliable and continuous elevation information is an important requirement of many mountain hydrology studies. In glaciology, elevation data across a glacier basin is required to determine the incoming solar radiation term, dependent on slope and aspect, when calculating surface energy balance. The area-elevation distribution (hypsometry) is necessary for extrapolating surface snow and melt measurements across the glacier basin when determining glacier-wide mass balance by the glaciological method (Østrem and Stanley, 1969). Calculating glacier mass balance by the geodetic method (e.g. Cogley, 2009) requires multiple elevation models that temporally span the period of interest. Further techniques, including glacier flow modeling, synthetic aperture radar interferometry derived measurements of velocity, and hydrological analysis, all require the input of elevation models. In this study, we focus on the hydrological analysis of glacier basins.

There are several remote sensing platforms that can provide elevation data with varying vertical resolutions and spatial coverage (Bamber and Rivera, 2006; Racoviteanu et al., 2007). Elevation data from the Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is particularly valuable for Arctic research as the latitudinal coverage extends to 83°N, surpassing the coverage of the Shuttle Radar Topography Mission (SRTM) that extended to 60°N. However, the noise level in ASTER digital elevation models (DEMs) can be significant enough to falsify measured elevation changes (Kääb et al., 2002). In this study, we attempt to improve ASTER derived elevation models using a mesh denoising algorithm designed to preserve edge features while lowering the noise floor of topographic data (Sun et al., 2007). We investigate the noise structure of the ASTER data and conduct ground validation tests of the processed elevation models using *in situ* elevation measurements from the glacier surface. Finally, we explore how the

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denoised elevation models perform when conducting hydrological analysis with ESRI's geospatial information system (GIS) software ArcGIS.

2. SITE DESCRIPTION

We have chosen to test the denoising algorithm over White Glacier, a 14 km long valley glacier located on Axel Heiberg Island, Nunavut, where previous elevation studies and ground-control data are available for validation of the processing results. It is one of only 37 reference glaciers recognized in the United Nations Global Terrestrial Network for Glaciers. This qualification was granted as a result of the 54-year mass balance monitoring program that has continued on a near annual basis since 1959 (Müller et al., 1963), making White Glacier the longest studied alpine glacier in the Canadian Arctic. While mass balance studies have taken precedent in recent years, White Glacier was the focus of a diverse spectrum of glaciological studies in the 1960-1970s that have included investigations of ice velocities and thickness, polythermal properties, surface energy balance, surface albedo, and lake drainage events (Cogley, 1999). Calculating the contemporary elevation distribution of White Glacier is an important component to updating the mass balance calculation parameters (Zemp et al., 2013).

3. METHODS

3.1 ASTER DEM

The along-track stereo imaging capability of ASTER in Band 3 (0.76–0.86 μm) allows for the production of elevation models through photogrammetry methods. The horizontal resolution of Band 3 is 15 m and the vertical resolution of the ASTER DEM ranges from 15 m in topographically flat regions, to 60 m in complex mountainous terrain (Kääb et al., 2002). In this study we use an ASTER DEM generated by NASA's Land Processes Distributed Active Archive Centre (LP DAAC) using stereo imagery acquired on June 11, 2010 (Figure 1). The stated vertical resolution of the product is 30 m and elevations in the vicinity of White Glacier range from 0 to 1800 m a.s.l. The area was snow-covered above 800 m and the acquisition exhibited no cloud cover over the region of study.

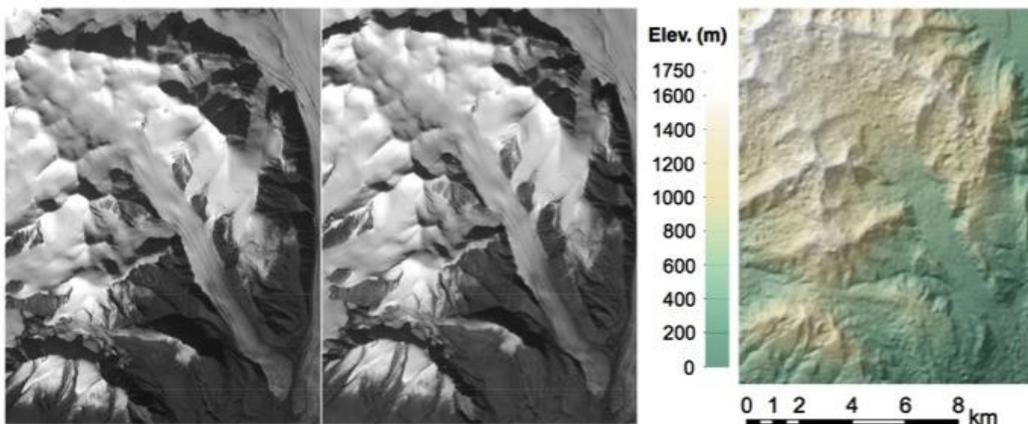


Figure 1. ASTER Band 3 Nadir (left) and Backwards (middle), and resulting ASTER DEM (right)

Acquired July 11, 2010

3.2 Mesh Denoising

The mesh denoising-algorithm designed by Sun et al. (2007) aims to preserve ground data while removing noise at the full spectrum of frequencies whereas, in comparison, smoothing functions generally focus on high- frequency noise. Sun's Denoising (SDN) algorithm operates in two stages. First, vectors normal to the surface are iteratively averaged using a weighted mean of neighbouring cells. Second, feature vertices formed by intersecting surfaces are updated to agree with the denoised planes. The algorithm requires two user defined inputs: (1) the number of iterations and (2) a threshold parameter defining the weight and spatial extent of the averaging. Running the SDN algorithm is computationally inexpensive, requiring between 3 and 8 seconds, dependent on the number of iterations, to denoise a 385 KB TIFF raster used in this study. The algorithm is freely available for interested members of the remote sensing community and can be accessed at: www.cs.cf.ac.uk/meshfiltering/index_files/Page342.htm

4. RESULTS AND ANALYSIS

4.1 Model Output

The 2010 ASTER DEM was post-processed with the SDN algorithm at feature sensitivity thresholds of 0.90, 0.95, and 0.99, and each 5, 10, 20, 40, and 80 iterations (Figure 2). Visual inspection of the processing results show that the level of smoothing decreases with the threshold value, and increases with the number of iterations.

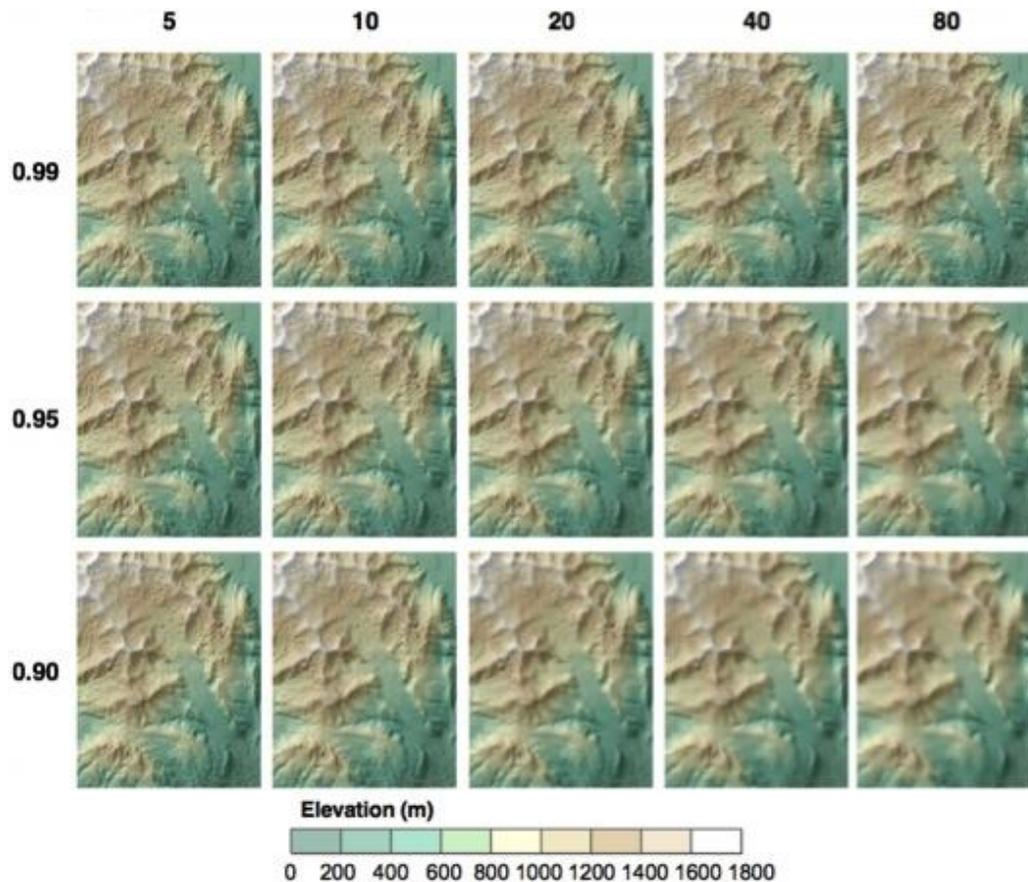


Figure 2. SDN algorithm results at a range of iterations (x-axis) and thresholds (y-axis).

4.2 Noise Structure

Differencing of the SDN analysis output and the raw ASTER DEM illustrates the magnitude and spatial structure of the noise correction (Figure 3). The emergence of topographical features in the noise correction indicates that these features are, incorrectly, being interpreted as noise by the algorithm and are vertically adjusted, primarily by dampening, by the model as a result. This is particularly evident in processing runs with threshold values of 0.90 and high numbers of iterations.

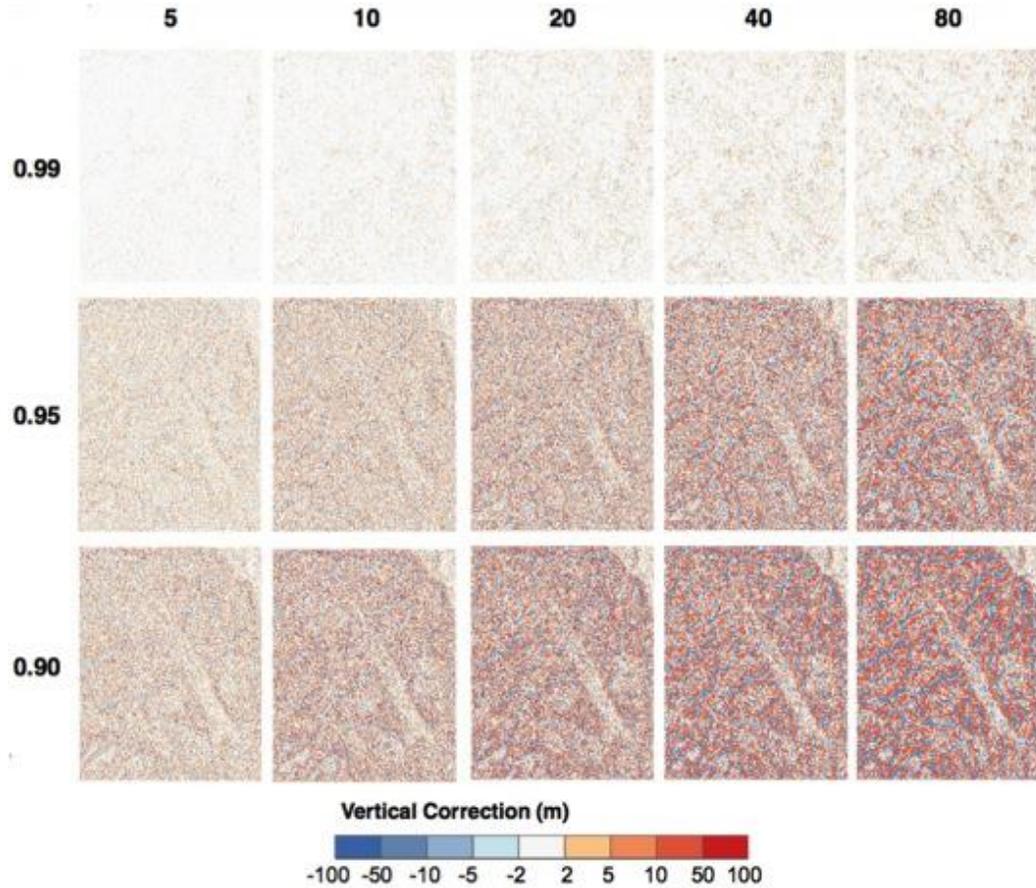


Figure 3. Vertical corrections applied by the SDN algorithm at a range of iterations (increasing from left to right along the x-axis) and thresholds (increasing for bottom to top along the y-axis).

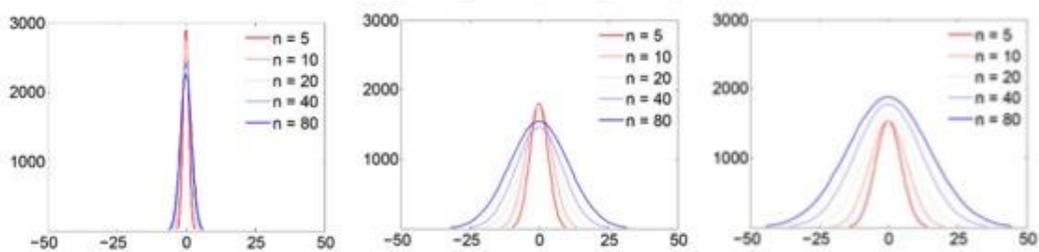


Figure 4. Probability distributions of vertical correction magnitudes (x-axis) and frequencies (y-axis) for threshold values of 0.99 (left), 0.95 (middle), and 0.90 (right) at a range of a number of iterations (n).

Statistical analysis of the elevation correction magnitudes imposed by the denoising algorithm were conducted to determine whether the method introduced a positive or negative vertical bias, which would be indicated by a mean of corrections significantly different from zero. The probability distribution curves (Figure 4) show, for each tested threshold value, that the average correction is centered near zero and that the standard deviation of the correction increases with decreasing threshold level. Specifically, calculated mean values of the corrections for thresholds 0.99, 0.95 and 0.90 were 0.008-0.011 m, 0.012-0.019 m, and 0.22-0.034, where the range of means for each threshold reflect the associated influence of the number of iterations. Similarly, the standard deviations of the corrections were 1.0-2.1 m, 3.2-11.3 m, and 4.6-15.6 m, for respective threshold values of 0.99, 0.95 and 0.90. The highest magnitude corrections approached 50 m (both above and below the original DEM) and resulted from SDN processing with a threshold value of 0.90 and at 80 iterations. For all thresholds, it is apparent that an increase in the number of iterations also increases the standard deviation of the applied corrections.

4.3 Ground Validation

The ground validation points were gathered approximately along the glacier centerline in the spring of 2012 with a Trimble R7 mounted on the back of a snowmobile (Figure 5, left). The reported dGPS elevations have been corrected for the antenna offset from the ground. To assess the vertical accuracy of the SDN corrected DEM we calculated the difference between the GPS elevation and the modeled elevation at the same geographic coordinate along the GPS track (Figure 5, right). It is also interesting to note the increasing variability towards the accumulation area (A'), which is presumably associated with poor contrast in the accumulation area, making feature correlation between the ASTER stereo images difficult when generating the raw ASTER DEM.

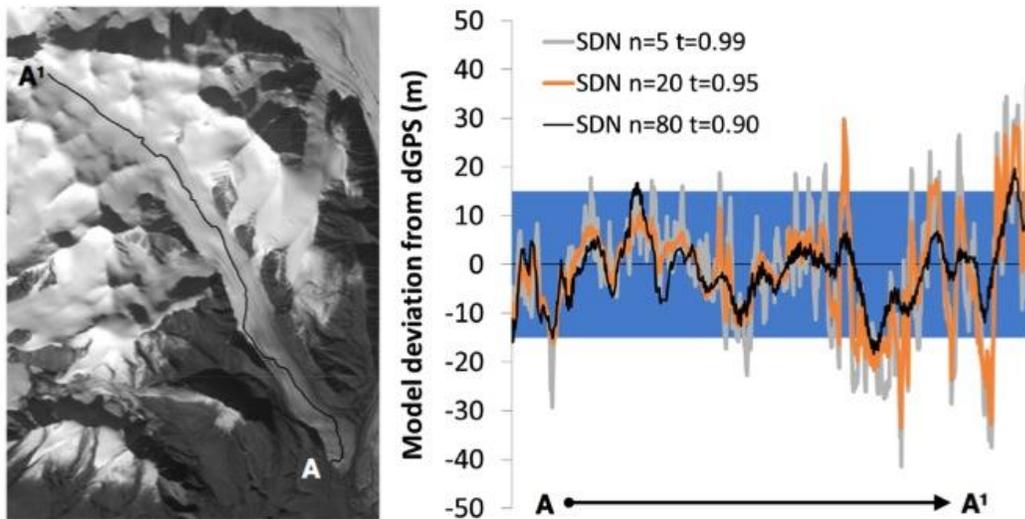


Figure 5. Left: Differential GPS track on White Glacier, April 25, 2012, from the glacier terminus (A) to the top of the accumulation area (A'). Right: Deviation of model elevations from the dGPS elevations. The region in blue outlines the vertical resolution of the original ASTER DEM.

4.4 Hydrological Analysis

Basin mapping in GIS requires removal of artefacts, such as topographic sinks, before basins and watersheds can be defined. Without any post-processing, the standard approach to dealing with topographic sinks is to apply a function that fills sinks. Applying such a function results in a

net vertical bias that artificially raises the elevation of the glacier surface. We use the ESRI ArcGIS Hydrology Toolset to detect surface sinks in the original ASTER DEM and in the output DEMs from the SDN algorithm processed at a range of thresholds and iterations (Figure 6). The number of sinks decreases substantially with more rigorous processing with the SDN algorithm (namely increasing the number of iterations and decreasing the threshold value).

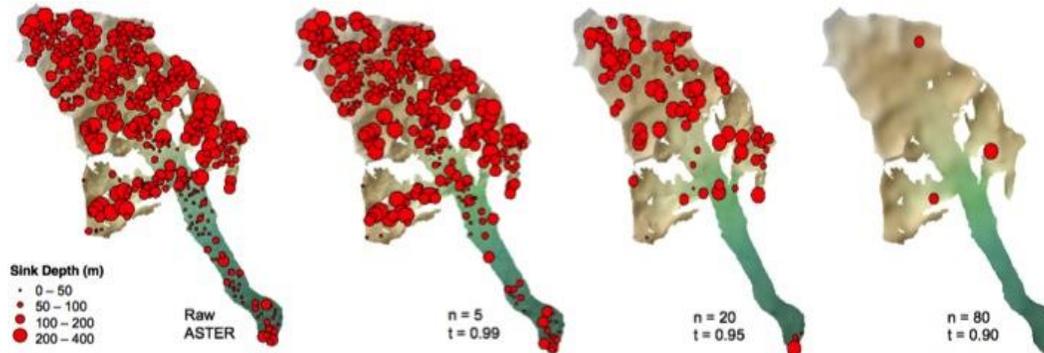


Figure 6. Topographic sinks present in the raw ASTER DEM and at varying levels of processing through the SDN algorithm

5. DISCUSSION AND CONCLUSIONS

We found that the denoising algorithm by Sun et al. (2007) can successfully reduce the noise level of ASTER DEMs without introducing a vertical bias in the data. For those interested in using the SDN algorithm, a few caveats must be considered. When selecting model parameters, a high threshold (0.99) preserves topographic features (e.g. peaks and ridges), but also allows high amplitude noise to pass through uncorrected. A low threshold (0.90) dampens topographic features, but successfully removes high amplitude noise. At all thresholds, an increase in the number of iterations leads to the reduction of high amplitude elevation features, both anomalous and topographically true (e.g. ridges).

Along the centreline of White Glacier the low level threshold (0.90) denoising function showed closest agreement with the *in situ* elevation profile within ± 20 m. It is apparent that the ASTER DEM shows increased noise in the accumulation area, which is likely associated erroneous features introduced due to the lack of radiometric contrast. The most rigorous correction parameters, with a threshold of 0.90 and 80 iterations, show the least deviation from the ground validation data. However, it is important to bear in mind that corrections by SDN are generally low along the glacier centerline and it is expected that these would deviate greatly towards local ridgelines where this level of processing misinterprets surface topographic features as noise.

Hydrological analysis conducted on the output DEMs from the SDN algorithm showed significant improvement compared to similar analysis on the original ASTER DEM. The number of topographic sinks reduced by an order of magnitude with DEMs output from rigorous processing under the SDN algorithm. It is expected that a dampening of the topographic features will not necessarily affect the calculation of flow direction and thus automated basin delineation, however this will be investigated further in future research.

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