Supplement for

[Bare-earth DEM Generation from ArcticDEM, and Its Use in Flood Simulation]

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Introduction

This document includes Text S1 which are the equations to calculate DEM error metrics, Table S1 which is the land use and land cover types and the percentage of each type for the study site of the city of Helsinki (sample S3), Figure S1 which is the surface plot of the ArcticDEM-SMRF error metrics against the window size and slope threshold parameters of the SMRF algorithm for sample S1 and S2, Text S2 is the corresponding analysis of Figure S1, Figure S2 which is the surface plot of the ArcticDEM-SMRF error metrics against the window size and slope threshold parameters at sample S3 for three slope categories, Text S3 is the corresponding analysis of Figure S2, Figure S3 which is the error distributions of ArcticDEM and ArcticDEM-SMRF for selected urban features, and Text S4 is the corresponding analysis of Figure S3.

Text S1.

RMSE, the Reduction of RMSE and the Mean error equations used in the ArcticDEM-SMRF error evaluation are outlined below.

$$RMSE_{DEM} = \sqrt{\frac{\sum_{i=1}^{i=n}(H_{i,DEM}-H_{i,LIDAR})^2}{n}} \quad (1)$$

$$RMSE\ reduction_{ArcticDEM-SMRF} = \frac{100\%\times(RMSE_{ArcticDEM}-RMSE_{ArcticDEM-SMRF})}{RMSE_{ArcticDEM}} \quad (2)$$

$$\text{Mean error}_{DEM} = \frac{\sum_{i=1}^{i=n}(H_{i,DEM}-H_{i,LIDAR})}{n} \quad (3)$$

*$H_{i,DEM}$ is the orthometric height at pixel i of the DEM, and n is the total pixel numbers. The DEM is the original ArcticDEM or ArcticDEM-SMRF in this paper.

Table S1. Land use and land cover types, reclassified categories, and their percentages for the inland areas of sample S3 for the city of Helsinki. The categories that represent the reclassified types are bolded followed by their subcategories.

Land use and land cover types	Percentage
Urban areas	65.40%
Continuous urban fabric (S.L. : > 80%)	2.58%
Discontinuous dense urban fabric (S.L. : 50% - 80%)	9.03%
Discontinuous medium density urban fabric (S.L. : 30% - 50%)	10.37%
Discontinuous low density urban fabric (S.L. : 10% - 30%)	8.34%
Discontinuous very low density urban fabric (S.L. : < 10%)	1.46%
Isolated structures	0.20%
Industrial, commercial, public, military and private units	11.63%
Fast transit roads and associated land	1.05%
Other roads and associated land	6.89%
Railways and associated land	1.28%
Port areas	0.37%
Mineral extraction and dump sites	0.64%
Construction sites	0.21%
Land without current use	0.30%
Green urban areas	7.57%
Sports and leisure facilities	3.47%
Forest areas	20.52%
Forests	20.51%

Herbaceous vegetation associations (natural grassland, moors...)	0.01%
Open land areas	10.87%
Arable land (annual crops)	5.82%
Pastures	4.75%
Wetlands	0.30%
Water	3.21%

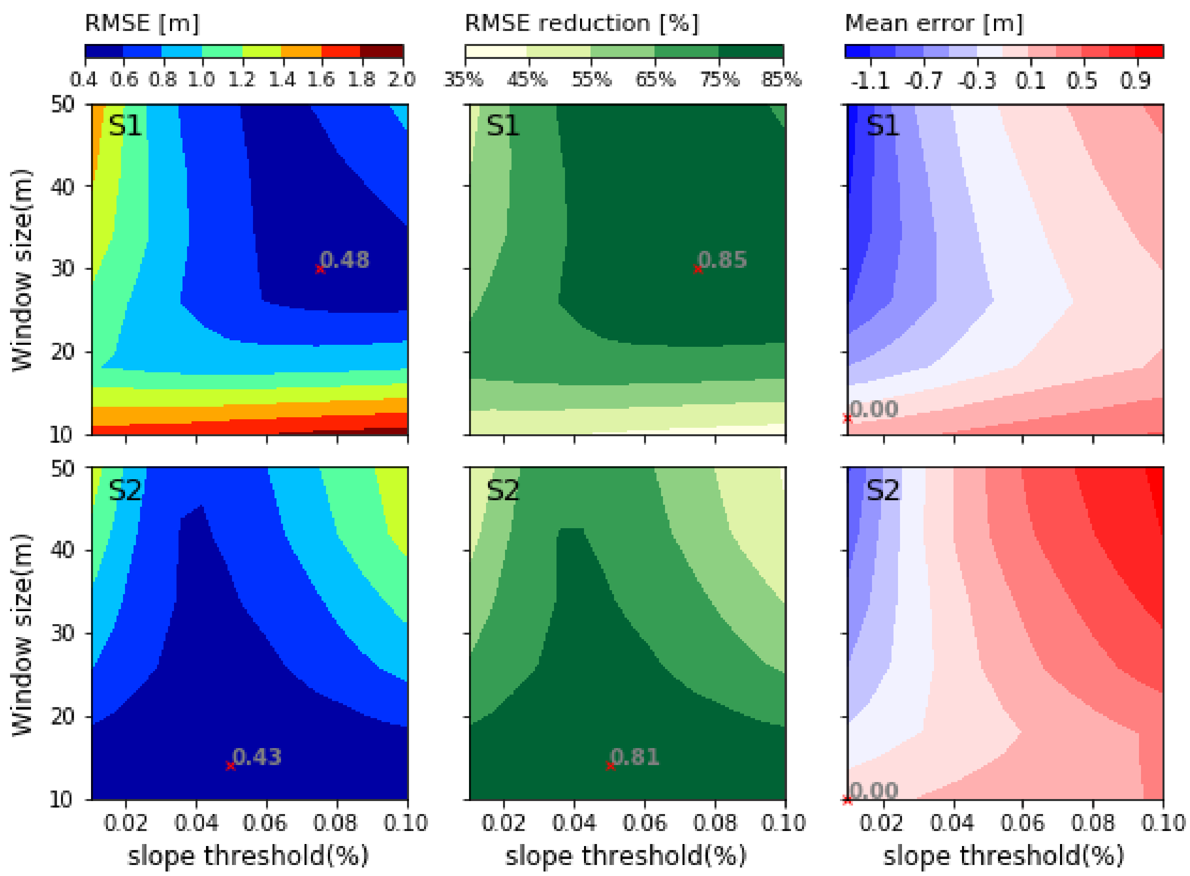

Figure S1. Surface plot of the RMSE, RMSE reduction and Mean error of the ArcticDEM-SMRF against the slope threshold and window size parameters of the SMRF algorithm for sample areas S1 and S2. The total number of parameter combinations in the ArcticDEM-SMRF ensemble is 399. The parameter ranges can be found in Table 1 in the paper's main text. The location of the smallest values of the RMSE, the largest values of the RMSE reduction and the smallest absolute values of the Mean error are marked as red crosses, with the values displayed. 5% data was excluded as outliers in the calculation.

Text S2.

The response of RMSE to filter parameter variation at both S1 and S2 presents as a 'bell-shape' (narrow top and wide bottom). This means that the slope threshold has a broader range at smaller window sizes. Among the parameter combinations that generate the ArcticDEM-SMRF with the smallest error, the most robust window size is defined as the size that allows the broadest range of the slope threshold. To achieve an RMSE of 0.4 - 0.6 m, the window size that allows for the broadest range of acceptable slope thresholds is ~25 m for S1 and 10-15 m for S2 (i.e., the most robust window size). When the window size is below 20 m, the reduction of RMSE for S1 is relatively small (<55%) regardless of changes in the slope threshold parameter. This suggests that a minimum threshold of window size exists. The different values of the most robust window size and the minimum slope threshold between S1 and S2 is a result of the building size differences between these two areas. The size of building artefacts also impacts the broadness of the parameter range. To achieve the largest reduction of the ArcticDEM error, target areas with large artefacts (such as S1) allow a narrower range of slope thresholds but a broader range of window sizes compared to areas with small size artefacts (S2). The slope threshold range is 0.06-0.1 for S1 in contrast to 0.01 to 0.1 for S2, and the window size range is between 25-50 m for S1 and 10-20 m for S2.

The sensitivity of the Mean error to variations in the SMRF parameters at S1 and S2 has a similar shape. The combination of small slope threshold (0.01-0.03) and large window size (25-50 m) generates ArcticDEM-SMRF with negative error, while the combination of large slope threshold (0.07-0.1) and large window size (35-50 m) generates ArcticDEM-SMRF with positive error. There is a certain window size beyond which the Mean error becomes more sensitive to the slope threshold. And the sensitivity of the Mean error increases with decreasing slope threshold. This window size threshold for S1 is between 20-30 m, and between 10 m-20 m for S2, which also corresponds to the most robust window size when considering the RMSE.

This sensitivity analysis indicates that rather a broad range of window size and slope threshold combinations achieve significant reduction in DEM error compared to the reference LIDAR data. The window size would ideally be determined with reference to the size of the majority artefacts of the target area and a slope threshold greater than 0.06 is suggested.

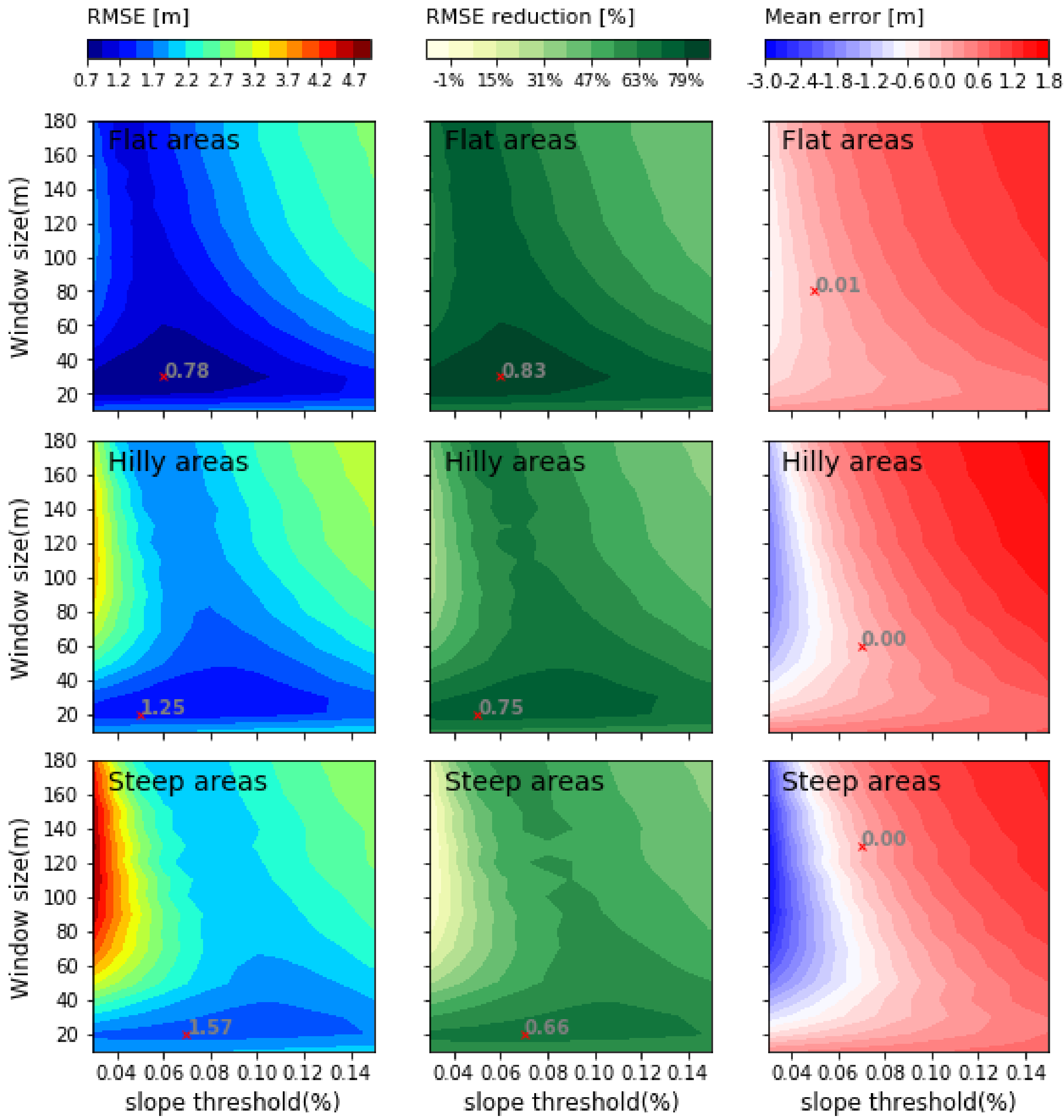

Figure S2. Surface plot of the RMSE, RMSE reduction and Mean error of the ArcticDEM-SMRF against the slope threshold and window size parameters of the SMRF for sample area S3 for different slope categories. The LIDAR DTM was used to calculate the slopes for Sample 3. Flat areas are defined as slope between 0 and 5º, hilly areas are defined as slope between 5 and 10º, and areas with slope larger than 10º are defined as steep areas. The total number parameter combinations tested is 234. The range of the parameters can be found in Table 1 of the paper's main text. The location of the smallest values of the RMSE, the largest values of the RMSE reduction and the smallest absolute values of the Mean error are marked as red crosses, with the values displayed. 5% data was excluded as outliers in the calculation.

Text S3.

Although the response of the ArcticDEM-SMRF ensemble to the SMRF parameters presents as similar shapes for the three slope categories, the error magnitude of ArcticDEM-SMRF increases and the RMSE reduction decreases from flat areas to steep areas. This means that the SMRF is most effective for flat areas. Additionally, with slope threshold smaller than 0.06, further reductions of the slope threshold introduces negative errors into the ArcticDEM-SMRF for areas with slope larger than 5° (hilly and steep areas), while the change of the mean error in flat areas is marginal. This relates to the character of the SMRF algorithm. For non-flat areas, the filter incorrectly identifies the slope as a surface artefact and the subsequent interpolation removes part of the natural terrain.

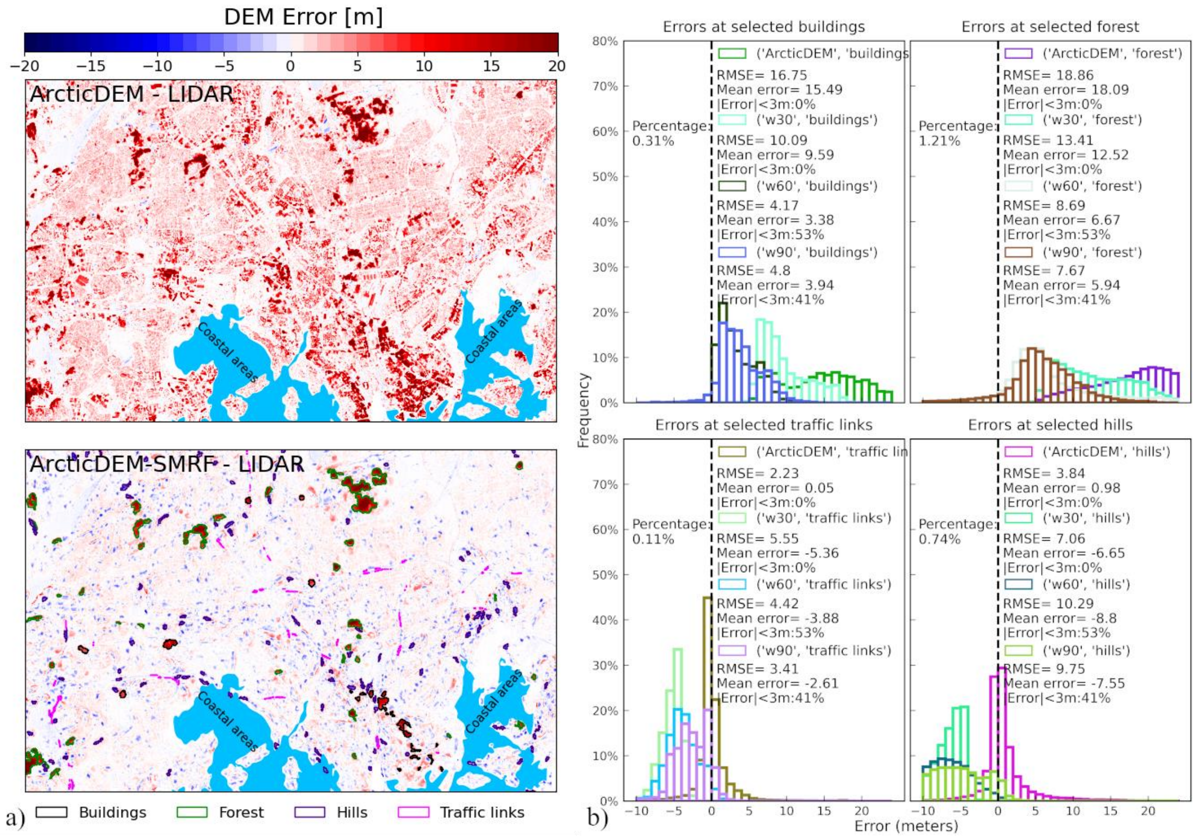

Figure S3. Error maps of ArcticDEM and the optimal ArcticDEM-SMRF (slope threshold = 0.07, window size = 30 m as SMRF parameters) and the error histograms of the original ArcticDEM, the ArcticDEM-SMRF filtered with some parameter combinations for selected urban features. All data are presented at 2 m spatial resolution. In the left-bottom map of a), example locations of residual errors of the ArcticDEM-SMRF errors are labelled. These locations represent four types of features: buildings, forest, traffic links and hills. Only patches with either large size (> 6000 m^2) or representing typical features were shown to improve the map clarity. The error histogram of the ArcticDEM, filtered ArcticDEM by SMRF with window size parameter at 30 m, 60 m, and 90 m (slope threshold = 0.07) of these selected areas are shown at b). The percentage of the selected features are calculated as the areas of those features divided by the overall areas without coastal areas.

Text S4.

Some examples of residual errors in ArcticDEM-SMRF are labelled in Figure S3. These examples were drawn from four feature types: buildings, forest, traffic links and hills. The area of these features represents no more than 1.2% of the overall land area. The error histograms of these features are also shown. According to the effect of the SMRF on these features, they can be divided into positive and negative error groups.

First, dense forest areas and closely-spaced buildings with large floor sizes show large positive errors (>5 m). Errors for these features were significantly reduced across a wide range of window sizes (30-90 m). The window size to achieve the minimum error for each type of feature is a function of the feature's patch size. This value is between 60 m and 90 m, but larger than 90 m for the selected forest areas. This means that the filter can flag these artefacts or part of these artefacts as objects correctly and the interpolation reduces the errors of the filtered DEM (ArcticDEM-SMRF). However, residual errors are difficult to eliminate for two reasons. First of all, a fixed window size would always result in the boundary of the object patches either being underesimated or overestimated by the SMRF. In the case of underestimation, a small number of pixels within the objects might be flagged incorrectly as ground and the subsequent interpolation step would employ these 'ground' values and cause residual errors. By employing an enlarged window size (the slope threshold is constant) the missed pixels from the object identification could be flagged correctly, however the interpolation step would still not be as successful as that for objects with small patch size. Taking all artefacts of the study site into account, an enlarged window size would cause more of the ground pixels to be identified as artefacts incorrectly (overestimation) and some details of the terrain would be lost, which would introduce negative errors to ArcticDEM-SMRF.

Second, large negative errors were shown in hilly areas (slope > 10º) and at some traffic links. As these features have similar characteristics to artefacts, they are usually identified as objects incorrectly by the SMRF filter and then wrongly interpolated by the inpainting algorithm. For example, the traffic links present as line-shaped, above-ground artefacts in the LIDAR DTM. In both cases, the filter at all window sizes fails to replicate the variation of the terrain of these features. Moreover, the ArcticDEM-SMRF error increased within these two types compared to the original ArcticDEM.