A Comparison of Aerodynamic Roughness and Surface Roughness Measurements Derived from Terrestrial Laser Scanning Over Ice and Sandar Surfaces

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1. Background

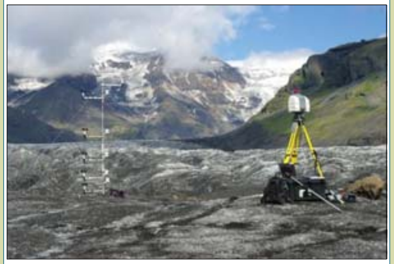

Fig. 1.1 TLS and wind tower on rock covered ice surface, Svínafellsjökull glacier, Iceland.

Surface roughness influences aerodynamic roughness which is a key component required for energy balance models in glacial and snow environments (Hock 2005) and sediment transport models in aeolian environments (Greeley & Iversen 1985). Quantifying surface roughness at high spatial resolution has often proven difficult in the past and traditional methods are time consuming and prone to manual errors (Brock *et al.* 2006).

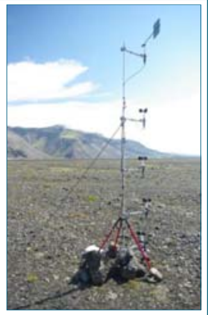

Fig. 1.2 Wind tower on an inactive sandur surface, Kota Sandur, Svinafell Iceland.

Terrestrial laser scanning (TLS) is an innovative, non-invasive surveying technique that produces accurate high resolution (mm) point clouds of topographic data. This research assesses the potential of using TLS to improve the parametrisation of small scale surface roughness. This is achieved by comparing roughness derived from TLS data with measured aerodynamic roughness (z_0) for a range of environments with varying topographic and surficial depositional characteristics.

3. Data Processing

Two methods were used to quantify surface roughness from the TLS data.

Moving Window Method
This method attempts to quantify surface roughness by passing a 'moving window' over surface DEMs and equates z_0 to the standard deviation of elevations (σ_z) of grid cells within the moving window, as used for alluvial fans by Frankel and Dolan (2007).

Transect Method
Two transect based methods were used to evaluate z_0. Six transects were extracted from each surface, three transects aligned perpendicular and three aligned parallel to the dominant wind direction.

1) The Kean and Smith (2006a,b) method approximates topographic elements along each transect as a series of Gaussian curves. These were manually fitted along each transect by defining the bump minima (Fig 3.1). The characteristics describing the Gaussian functions were extracted from each profile, where *H* represents the height of protrusions, *σ* the streamwise length of the features and *W* the crest spacing between protrusions (Fig 3.2). These parameters were combined to produce useful measures from which to evaluate surface roughness.

2) The same transects were also used to calculate z_0 using the method of Lettau (1969), employed in studies by Munro (1989) and Brock *et al.* (2006), where:

$$z_0 = 0.5h^* \frac{s}{S}$$

In the above expression h* is the average protrusion height (twice standard deviation of detrended elevation), s is the silhouette area and S is the unit ground area.

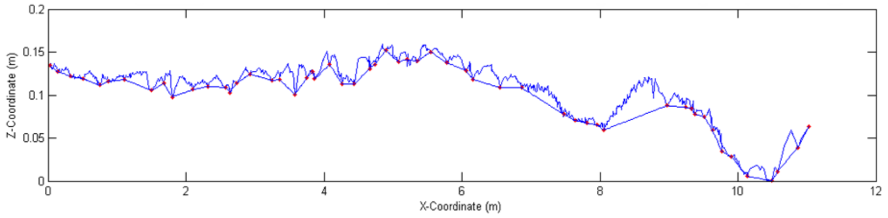

Fig. 3.1 Gaussian curves fitted along a transect by defining the bump minima

2. Study Site and Methods

Four characteristic surfaces were surveyed using a Leica Scanstation in Svinafell, Austur-Skaftafells, Iceland between the 6th and 11th July 2011; a) rock covered ice and b) ash covered ice were studied on Svínafellsjökull glacier and c)an inactive sandur (Kota Sandur) and d) an active sandur (Falls Sandur) (Figure 2.1). At each site scans were collected with mean point densities ranging from 26,000 - 1,200 pts/m². A wind tower was set up at each site with five cup anemometers (~at 0.09, 0.52, 0.96, 1.58 and 2.41m above the surface) which automatically logged velocities at 5 second intervals for the duration of the research.

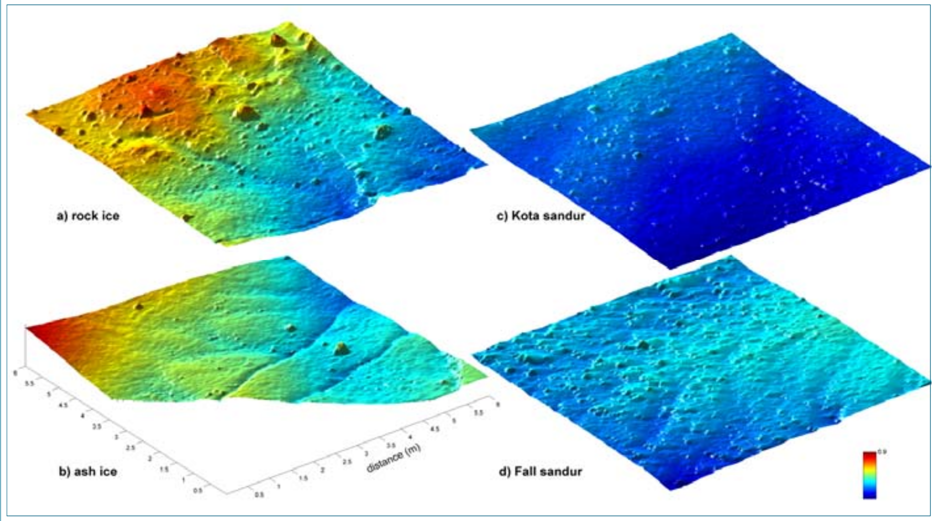

Fig. 2.1 Interpolated surfaces from the TLS data of the different sites surveyed.

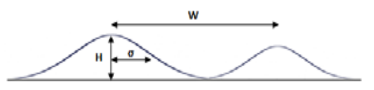

Fig. 3.2 a Definitions of the Gaussian fit parameters extracted from the profiles

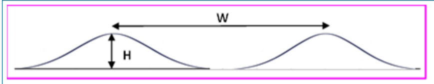

Fig. 3.2 b For W/H higher values indicate the distance between protrusions is greater than the height of protrusions

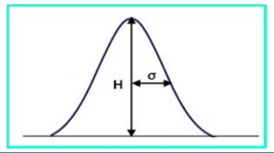

Fig. 3.2 c For H/ σ higher values indicate the height of protrusions is greater than the width of protrusions

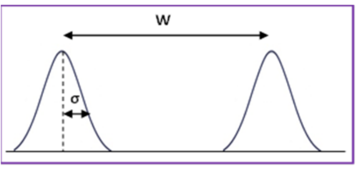

Fig. 3.2 d For W/ σ higher values indicate the distance between protrusions is greater than the width of protrusions

Aerodynamic Roughness
Aerodynamic roughness was calculated for coincident wind events, when the lower anemometer was > 1ms⁻¹ for a sustained period (> 30 min). During each of these events, one-minute average velocity profiles were used following standard law-of-the-wall profile methods to calculate aerodynamic roughness heights using logarithmic fits with R² values exceeding 0.97. Displacement lengths of 2/3 the mean height from the transect method were used to account for the larger sandar surface roughness elements (Oke 1987).

4. Results

Table 4.1 shows the mean value of the different measurement parameters calculated to quantify surface roughness together with the aerodynamic surface roughness values for each site. The location of the transects at each site were not found to have a significant effect. The maximum Lettau values were used as mean values were found to conceal surface roughness variations.

The four parameters with the strongest correlation to measured aerodynamic roughness are shown for each site on Figure 4.2.

Measuring Parameter	Fall Sandur	Kota Sandur	Rock Ice	Ash Ice	Correlation coefficient
z_0 (m)	0.008	0.006	0.005	0.001	
Bump Height (H)	0.019	0.013	0.021	0.018	-0.140
Bump Length (σ)	0.036	0.034	0.058	0.072	-0.9
Bump Crest Spacing (W)	0.154	0.127	0.153	0.234	-0.91
Frontal Area	0.004	0.002	0.004	0.007	-0.86
W/H (Spacing)	0.227	0.151	0.277	1.234	0.83
H/σ (Size)	3.728	4.697	4.184	7.229	0.95
W/σ (ratio of spacing to size)	6.346	5.588	5.460	4.205	0.98
Standard Deviation	0.003	0.002	0.004	0.007	-0.93
Lettau Equation (max. result)	0.002	0.001	0.002	0.001	0.72
Moving Window	0.020	0.009	0.023	0.017	-0.04

Table 4.1 All measurement parameters calculated to infer z_o

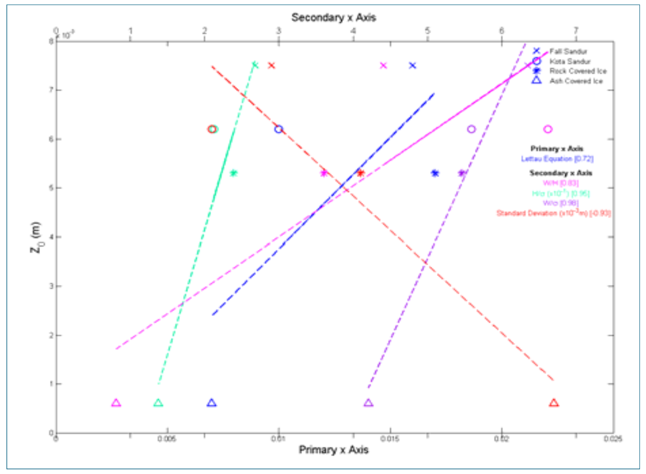

Fig 4.2 Relationship between shape parameters and aerodynamic roughness

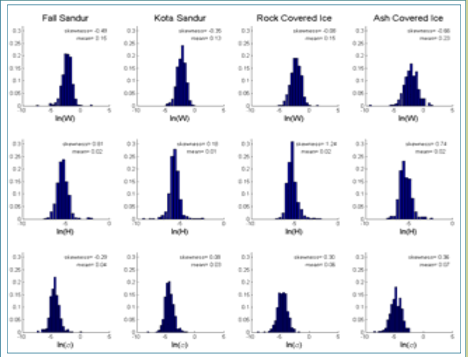

Fig. 4.3 Histograms of Gaussian fit parameters for each site

Histograms indicate the full distributions of the Gaussian fit parameters and reveal they conform to assumed log normal distributions. Important combinations of H, σ and W are plotted, where H/σ is the primary measure of the shape of the fitted elements and W/σ is the ratio of the two streamwise length scales (Figure 4.3 and 4.4).

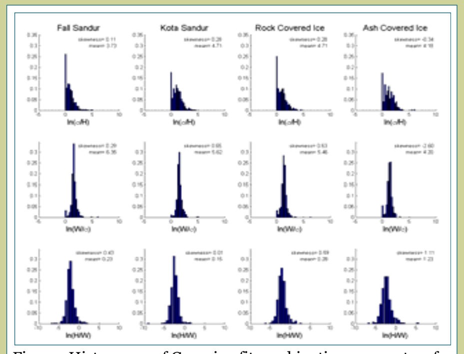

Fig. 4.4 Histograms of Gaussian fit combination parameters for each site

5. Discussion

Fig. 4.2 shows that W/H, H/σ and W/ σ correlate well with z_0 and suggests these parameters are good indicators of relative aerodynamic roughness trends. The Lettau values exhibit a weaker correlation. Table 4.1 shows the moving window values do not have a significant correlation with z_0 and suggests that other shape parameters are needed, together with protrusion height, to correctly calculate surface roughness. The negative correlation of the standard deviation of residuals (skin friction component of shear stress) with z_0 can be explained by the 'curdled' effect of the ash on the ice surface (Fig. 5.1). The skin friction component of the shear stress was greatest on the ash covered ice and smallest on the sandar. However, z_0 is predominantly determined by form roughness at all sites.

Fig. 5.1 The 'curdled' effect of the ash on the ice surface, Svinafellsjökull glacier, Iceland

Future Work…
The results from this study show that W/H, H/σ and W/ σ can be used to infer aerodynamic roughness. Future research should focus on incorporating the shape and frequency of protrusions within the moving window analysis. This would overcome the subjectivity of fitting Gaussian curves manually.

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