Answers to Reviewer #2

Reviewers comments are shown in black, authors' answers in blue, and there the line numbers refer to the revised version.

The authors presented a snow surface albedo model with small-scale surface roughness being considered. The model was constructed by combining the bulk volume albedo model (TARTES) with a surface scattering model based on the photon recollision probability theory. Overall, the manuscript is well written. Nevertheless, I agree with Picard that the authors should discuss their results with respect to the recent literature like Larue et al. 2020 to further improve the manuscript.

The authors definitely agree with the reviewer that the paper by Larue et al. 2020 should be discussed. This paper was not available, when writing of the manuscript was started, but this paper is really interesting and is now added to the list of references and assessed in the introduction and discussion.

Detailed comments:

Line 131: rms -> root mean square?
Yes, this clarification is now added in the text in line 133.

Line 131-141: This section is not clear. Elaborate more about "the rms height and correlation and their distance dependence". It would be helpful if the authors can make a schematic diagram to illustrate the parameters and variables (the distance x and the correlation length L) in equation (1) and (2). In addition, explain "The snow surface roughness is close to a Brownian fractal surface" with more details.
The correlation length L is one of the basic descriptors of surface roughness. And x stands for the length of the analyzed profile. It is intuitively clear that if one wants to describe the roughness of 1 m, 10 m and 100 m long profiles, one will get different numerical values for the roughness parameters, such as rms height, as no natural (or man-made either) surfaces are stationary. The text is slightly edited to make it clear that x is the distance for which the surface roughness parameters σ and L are calculated. However, this roughness analysis is already more thoroughly explained in the given references (Manninen, Physica 2003; Anttila et al., JGR 2014), hence repeating it again (including diagrams) in an already long paper does not seem justified, but additional fundamental references are now included in line 134 (Keller et al., 1987; Church, 1988) and the text is slightly modified to help the reader to find this information.

The Brownian fractal surface is a fundamental term in surface roughness description not introduced for the first time in this manuscript. It is governed by Eqs. 1 and 2 already given in the manuscript. If the surface in question obeys those equations, it is Brownian fractal. However, the authors added a basic reference for Brownian fractal surfaces (Russ, 1994) in line 142 for an interested reader.

Line 144: "The vertical resolution was about 0.1 mm and the horizontal resolution 0.04mm." These two resolutions, you mean precision? It is a bit confusing with the context"...calculated for the measured spatial resolution, which was on the average 0.26 mm."
Yes, the term resolution is now replaced by precision in line 145.

Line 150-156: what is the exact data acquisition precision for your dataset? How does it compare with the plate measurement precision and resolution?

The acquisition precision of the laser data is thoroughly analyzed and described in the given reference Kaasalainen et al., The Cryosphere, 5, 135–138, 2011. They state that "The standard deviation of the average of the 212 corresponding points from each profile increased linearly as a function of distance from about 0.7 mm at 3 m to about 2 mm in 11 m, which indicates that the system is capable distinguishing the surface roughness features in the (sub)millimetre scale."
In this manuscript the text in line 155 is edited to provide the information: The absolute precision of these measurements was analysed by Kaasalainen et al. (2011) to be better than 5 cm, while the relative accuracy (which is more relevant for observing the snow roughness) was found to be 0.7 mm – 2 mm for a static system, and better than 10 mm when the snowmobile was moving.

The plate method precision is analyzed in the paper Manninen et al., Journal of Glaciology, 58(211), 993–1007, 2012 and the text line 146 is edited to state: The vertical precision was about 0.1 mm and the horizontal precision 0.04 mm.

Line 158-160: Is it possible to provide a figure to show the snowmobile tracks? and one scanned profile? How was "the root mean square (rms) slopes per size of horizontal distance increment" calculated? What's the unit?
The snowmobile tracks are already published in Figs. 1 and 2 in the given reference Kaasalainen et al., The Cryosphere, 5, 135–138, 2011 and in Figs. 1 and 3 in the reference Kukko et al., Cold Regions Science and Technology, 96, 23-35, 2013. Examples of the laser scanned profiles (and plate profiles) are also shown in the reference Kukko et al., 2013. To help an interested reader to find this information, the text is accordingly slightly edited in line 154.

The rms slope calculation is now described in detail starting in line 162: The slope angles for successive points were determined for each scan of the whole data set. The slope angles were then binned according to the horizontal distance between the successive points, with a bin width of 10^{-5} m. Then the root-mean-square value of the slope angles was determined for each horizontal distance bin and a regression function for the dependence of slope angles on distance between successive points was derived. The slope angles are presented in degrees (Figs. 6 and 7), as they are more illustrative than radians.

Line 209: per cent -> percent
Edited as requested.

Line 212: "complemented by set or artificial light measurements", typos?
Yes, the typo is now corrected.

Equation (4): please make the equation and the description of variables consistent.
Upon the request by Dr. Picard in the short comments the number of reflections of single photon and an ensemble of photons are now explicitly denoted differently: *n* and *m* for single photons and $\langle n \rangle$ and $\langle m \rangle$ for the ensemble means. The Eqs. 3 and 4 are revised accordingly.

Line 313-314: provide the surface height distribution histograms like figure 4.
Figure 4 is revised now to include both the rms slope and the surface height distributions.

Equation (7) and (8): give a detailed description of each variable shown in the equations.
It is checked that all variables are now given, θ_i and θ_o were added.

Line 356-369: This section involves lots of statistical correlation analyses between surface roughness parameters and surface albedo measurements. Please provide the scatter plots as supplementary material to show the correlations. The authors used the rms height as the only explanatory variable to explain the variability of albedo and obtained quite high R square and therefore concluded that "This result supports theview that surface roughness affects the albedo." I don't think this is a solid statement given that the snow grain size variations from March to April could greatly affect the variability of surface albedo. Without controlling for the snow grain size, it is not plausible to validate the relationship between rms slope and surface albedo. The authors should take both rms slope and snow grain size as the explanatory variables to explain the variability of surface albedo, and then compare the relative contributions of rms slope and snow grain size.

Scatterplots related to the text are now shown in the supplementary material document.

Definitely grain size variation from March to April affects the albedo, that is known in advance. Although both the surface roughness and grain size on the average increase with aging of the snow, the roughness does not depend only on the grain size. Otherwise there could not be any anisotropic surfaces, which typically appear because of the wind. The statistical correlation of Figure 8 is not said to be a proof of causality, it just supports the view that surface roughness affects the albedo and hence motivates closer analysis of the surface roughness and albedo relationship. The text is slightly edited in line 394: While correlation is not a proof of causality, this result supports the view that surface roughness affects the albedo.

Carrying out simple regression with both surface roughness and grain size is not worth doing, since the effect of those parameters on albedo is much more complex than a linear regression would show. (Besides, with grain size one would have to consider, whether to use only the surface grain size or also the grain size values deeper down in the snowpack.) Hence, the united analysis of grain size and surface roughness is carried out using the TARTES model (grain size) and the photon recollision model (surface roughness) as shown in section 3.

Discussion: according to the analysis, it appears that the spatial scale matters when evaluating the impact of surface roughness to snow albedo. Based on the results, can the authors discuss the implications of this study for studying the snow albedo changes using satellite data of different resolutions? Is there a rough estimate on how much surface roughness would affect the satellite albedo (such as MODIS albedo)?
This question is really interesting, but one would need a whole new study to answer it properly.

The scale matters when estimating the numerical values for rms slope angles, which are completely scale- dependent. However, in general snow is fractal and the surface roughness can be characterized with scale-independent variables (a, b, k of Eqs. 1 and 2).

If the satellite pixel consisted of an ideal plane of, for example, 100 x 100 one square meter patches of snow with equal properties, the satellite would observe the same albedo for the whole pixel as is measured in situ for a one square meter patch. But the question is, what happens to a pixel of (fractally) undulating surface. The surface roughness effect may then be larger, when one takes into account also others roughness scales than the smallest scale.

To summarize: the principle is the same in satellite resolution, but the question is, how to estimate the multiscale average number of facet-to-facet scattering. The effect may be slightly larger in satellite resolution than at in situ measurement resolution, but probably typically not radically, because of the fractal nature of snow. Because the rms slope angle decreases with increasing scale, it is expected that facet-to-facet scatterign events across large horizontal distances are rare. Maybe a second order effect would come from including larger spatial scales?

The following text is added to the end of the discussion section:
An interesting question is how the impact of surface roughness depends on the horizontal scale, especially considering the resolution of satellite measurements. It is expected that for an ideally flat surface, the impact of roughness would be essentially the same at the satellite resolution as that in the scale of in situ measurements. However, the larger the satellite pixel is, the larger spatial scale roughness has to be taken into account. The derived model is applicable to take into account roughness of all relevant scales, but the problem is how to estimate the average multiscale number of facet-to-facet scattering events. It is anticipated that due to the fractal nature of snow the small scale estimate of the average number of facet-to-facet scattering events is a reasonable first order estimate for the corresponding multiscale value, but a related detailed analysis is beyond the scope of this study.

Figure 3. Please label the figure to indicate the meaning of each different line.
Edited as requested.

Figure 11. For the April data, it appears that the uncertainty was dramatically increased after Julian day 112, any possible reason?
The temperature of the snowpack was below zero during the first measurement days in April, numbered 40-42 from the beginning of the campaigns, (i.e. Julian days 110-112) despite of the air temperature being above zero in the Julian days 111 and 112. However, in the Julian days 113-118 the temperature was zero at every depth measured in the snowpacks. Below is a figure showing the air and snowpack temperature values measured in April 2009 (SNORTEX II). The figure below is provided in the reference Manninen and Roujean, 2014. A comment related to this phenomenonon is added in line 444.

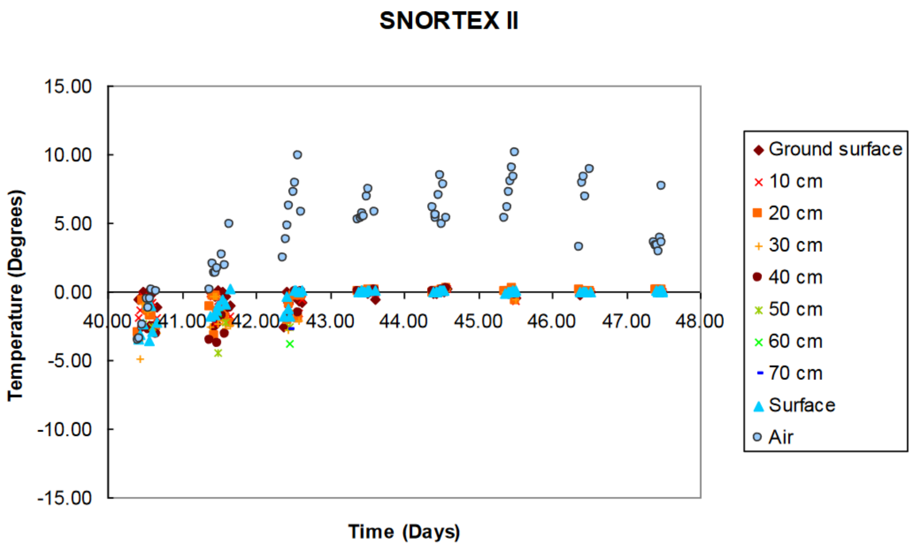

Figure 13. Shrink the Y axis scale to 0.5~0.8 instead of using 0-1, otherwise, the measured albedo seems to be constant through the time.
The Y axis is now shrinked to make it clear that the measured albedo is decreasing, as pointed out by the reviewer. The stepwise decrease in the modelled values is due to the limited accuracy the grain size estimation (¼ mm).

Figure 14. Are there three different profiles for the “rough” surface? If so, label therough profiles differently (different parameters)?

There are three different rough snow locations, each having a few profiles. They are now made distinct, but they go quite a lot on top of each other.