March 4, 2019

Dear Dr. Chambon,

We are grateful for the referees' time spent providing helpful comments and suggestions. In response to their reviews, we restructured and changed the title of the manuscript (tc-2018-198) to *Monitoring of Snow Surface Near-Infrared Bidirectional Reflectance Factors with Added Light Absorbing Impurities*. Furthermore, we now present our key scientific results that were originally going to appear in a separate paper.

In the following attachment, we respond to the referees' comments. We begin with our response to Anonymous Referee #3's general and specific comments. Next we address the detailed comments by Anonymous Referee #2. Finally, we respond to specific and minor comments from Dr. Dumont. We hope you find that our revised manuscript addresses the main concerns, inherent problems, and recommendations raised by all three referees, some of which are no longer relevant.

We look forward to your final decision regarding the acceptance of this manuscript for publication in *The Cryosphere*.

Sincerely,

Adam Schneider
amschne@umich.edu

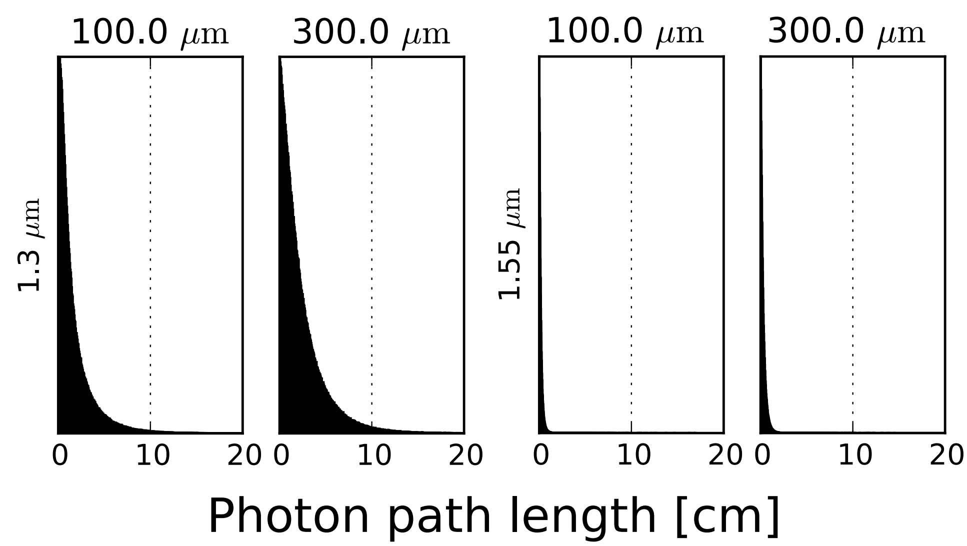
We are thankful for Anonymous Referee #3's review. To summarize, Referee #3 brought to our attention three critical flaws with the manuscript. First, they identify that the overall tone of the manuscript presents the The Near-Infrared Emitting and Reflectance Monitoring Dome (NERD) as a novel instrument that will eliminate the need for other similar instruments. They also point out an alarming over-simplification in the background presentation of previous snow specific surface area (SSA) measurement methods. These critical flaws are, to some extent, inherent from a lack of quantitative uncertainty analysis in the results and discussion. We generally agree with these criticisms and rewrote the manuscript accordingly.

In addition to renaming the manuscript, we refocused the primary objective on better understanding how light absorbing impurities (LAIs) affect snow albedo feedbacks. The revised manuscript better presents the NERD as an instrument that measures snow bidirectional reflectance factors to approximate snow SSA. Here, we apply the NERD specifically for the purpose of monitoring hourly scale snow surface microphysical properties with and without added LAIs. In light of this repurposing, the revised manuscript avoids language that implies that the NERD is validated as a precise snow SSA measurement method. Furthermore, we added new results from our LAI in snow experiments and discuss our findings in the context of the NERD's limitations. Following are our responses to Reviewer #3's comments, which are italicized for reference:

1. *Validation of the NERD measurement principle would entail comparing snow SSA values measured with the NERD to independent SSA measurements, e.g., SSA measured by other optical measurement methods or by methane gas absorption (or at the very least a vast number of CT measurements that are not used for developing the NERD measurement method). The authors have merely shown the consistency of BRF measurements (not SSA measurements) performed with the NERD on highly uniform, diffusely scattering reflectance standard surfaces. Neither the effects of extensive volume-scattering in snow nor possible directional/specular effects at the snow surface are included here. For example, is there light leakage into or out of the NERD on uneven surfaces, and what effect do oriented surface structures (small dents or ripples on the surface) have on measured BRF (I would expect this to be of greater concern here than for previously presented methods that are based on diffuse instead of directional reflectance)?*
Furthermore, no systematic and quantitative uncertainty assessment of snow SSA measurements with the NERD is presented (although the impact of various sources of uncertainty on measured BRF is discussed), which is an integral part of any presentation of a novel measurement method, as described in the 'Guide to the expression of uncertainty in measurement', for example. Particularly an inter-comparison of multiple measurement methods or comparisons of in situ and remote sensing observations, as alluded to in the conclusions of the manuscript, require a thorough assessment of the uncertainties affecting each measurement method to allow drawing reliable conclusions from such comparisons. In this manuscript, only a rough estimate of the variability of an empirically derived exponential relationship between BRF and SSA is interpreted as SSA measurement uncertainty, based on a low number of sample measurements. For empirical measurement methods, i.e., measurement methods that are not based on physical measurement models but on statistical correlation as presented in this manuscript, a large number of samples is required to guarantee a high statistical significance. A low number of samples can easily lead to highly underestimated (or overestimated)

measurement uncertainties over the entire or parts of the measurement range, especially when not validated against independent measurement methods.
A detailed NERD SSA measurement uncertainty assessment and validation would also include how the mismatch between CT measurement volume and NERD measurement volume affects the analysis. While suggesting to use the NERD to determine the large-scale spatial variability of snow SSA, the authors fail to discuss this very effect at a small scale of 10 cm, relevant for the NERD measurement principle, e.g., how do CT samples and NERD measurements match on the probed snow blocks, did they use enough CT samples to provide a reasonable estimate of the spatial variability within the snow volume probed by the NERD, did they only use the very top of the snow samples for their CT analysis because only this part is probed by the NERD due to the long NIR wavelengths of its illumination sources?

First, the lack of an independent SSA measurement method to validate NERD SSA measurements is a fundamental flaw in the presentation of the instrument. In the revised manuscript, we add limited results from contact spectroscopy measurements to determine optically derived snow SSA. These new results are included in Fig. 5. and discussed in the text toward the end of section 3.1.
Second, the effects of extensive volume-scattering within the snow are ignored in the context of the NERD snow BRF retrieval. Neglecting extensive volume scattering in snow, while it may be more relevant to other wavelengths, is purposeful here. Volume scattering is explored using three dimensional Monte Carlo modeling. In fact, these modeling results indicate that photons at 1.30 μm (and 1.55 μm) undergo an order of magnitude or two fewer scattering events than shorter, visible wavelengths. Furthermore, we estimate that the most of these photons' path lengths are limited to just a couple centi-meters within the upper-most layers of the snow pack, as demonstrated by the below histograms.



These histograms show Monte Carlo photon path lengths simulated in snow. In the model, snowpack is represented by a matrix of homogenous, randomly oriented aspherical ice particles suspended in air. Particle sizes (100, 300 μm) are defined by their sphere equivalent radii, calculated from their projected areas.
Because of these results, we assume that in the most general case, the snow bidirectional

scattering-surface reflectance-distribution function (which includes subsurface volume scattering) is well approximated by the simpler snow bidirectional reflectance distribution function. While this assumption would not be valid for visible and shorter near-infrared wavelengths, we believe this assumption is valid at 1.30 and 1.55 μm. This is also why we often use the term "reflectance factor" to describe our measurements.

Excess ambient Light into the field of view of the NERD photodiodes is accounted for by subtracting dark current from photodiode current measurements. Measurements are collected continuously so that the displayed BRF is representative of the previous 5-10 seconds worth of measurements. Therefore, this procedure yields accurate BRF measurements only after not moving for roughly 5 seconds. If the environmental conditions are changing rapidly, e.g., when clouds are moving in and out of view of the sun, then BRF measurements are unreliable.

Micro-scale ripple / lens effects strong enough to have a measurable impact on the NERD are of interest but beyond the scope of this study. Assuming these effects lead to measurement uncertainty for directional reflectance retrieval, we attempt to minimize this uncertainty by using multiple infrared emitters and photodiodes spanning four zenith / azimuth angle combinations. In the manuscript, all snow BRFs presented represent medians or means of as many as eight samples obtained from two independent viewing azimuth angles and also from rotating the dome.

Third, the manuscript is poorly structured and is unfocused. This ambiguous purpose leads readers to believe that the results and discussion present the NERD as an instrument capable of obtaining precise snow SSA in applications beyond the scope of the revised manuscript. While accurate, precise snow BRFs can be measured in favorable conditions, limited evaluation and validation of snow SSA retrieval cannot be assumed from the presented results.

In response to this critical flaw, we repurposed the entire study, as stated previously, and limit our discussion of NERD derived snow SSA results to our LAI in snow experiments. We present these results in the context of a large uncertainty range, provided by the error bars in Figs. six and seven, and alongside CT results for comparison. As pointed out by the referee, a full NERD snow SSA validation would entail far more samples and additional measurement methods.

Because the primary study of the revised manuscript is on LAIs' influence on snow albedo feedbacks, we only partially address the above criticism by showing a small number of data points from contact spectroscopy measurements in Figure 5. These SSA data are colored consistently with the snow samples they represent, but marked by hollow triangles for depth hoar (blue) and rounded grains (pink).

Finally, the manuscript fails to address how closely the NERD-probed snow samples relate to those collected and placed into the micro-CT machine. This point highlights one of the main difficulties associated with the comparison of NERD snow measurements to micro-CT snow samples. Getting the same snow that was targeted with NERD into the micro-CT machine is challenging, yielding inherent uncertainty in the precise determination of snow SSA using the presented NERD calibration function. Without access to other instrumentation that will operate in the field, it is nearly impossible to perform an apples to apples comparison of snow measurements. This is also one of the main motivations for developing this instrument. But a more complete SSA calibration remains challenging.

In response to these inherent uncertainties, we attempted to collect just the top few centimeters of snow closest to that probed by the NERD, as suggested by the referee. For best results, snow samples collected just outside of the Cold Regions Research Engineering Laboratory were transported directly into the micro-CT machine immediately following NERD measurements. Ironically, results from these "best" comparisons yield weaker correlations between NERD BRFs and CT SSA than our other comparisons.

Because of the inherent uncertainty with deriving snow SSA from NERD BRF measurements using X-CT for calibration, the revised manuscript generally avoids discussion pertaining to the precise determination and demonstration of snow SSA. Instead, we now focus on the demonstration of large, highly likely, changes in surface snow behavior at large after adding LAIs. These significant changes are detectable by the NERD and are complemented by CT.

2. *Without validation of NERD SSA measurements, and thus without an essential part of any presentation of a novel measurement method, some of the made statements seem rather unfounded. For example, the authors seem to repeatedly suggest that the NERD can accurately measure BRFs for snow, but how do they know that? Only BRF measurements on reflectance standards are somewhat validated as their nominal reflectance values are known and as they are roughly compared in this manuscript to reflectance measurements of reflectance standards that were performed with previously presented measurement methods. Going on to claim accurate snow SSA measurements based on these basic results and without any quantitative validation seems to be even more unfounded than claiming accurate snow BRF measurements.*

   The authors also stress the high cost of other snow SSA measurement methods and the low cost of their anticipated NERD instrument. Yet, I fail to see how the development of a useful measurement tool in the field based on their measurement principle will lead to a price of the instrument of less than thousands of USD, similar to the cost of some of the other optical measurement methods that can be used to derive snow SSA. Can the authors give a realistic cost estimate to justify such claims, factoring in development, prototyping, weather sealing, installation of permanent and sturdy components, ... of a portable NERD measurement tool? If they mean the NERD will be cheaper than a CT or a high-resolution spectrometer, then they should not overly generalize by including all previously presented measurement methods in this statement, while they actually only talk about some of those (see also point 3 below).

   First, we believe the NERD is capable of obtaining accurate snow BRFs at 1.30 and 1.55 μm because of the relatively small photon path lengths here compared to shorter wavelengths. This reasoning is fully addressed in the response to comment one. In short, assuming that the snow bidirectional surface-scattering reflectance-distribution function is well approximated by the snow bidirectional reflectance distribution function, the effects of volume scattering can be ignored. In response to this point, we renamed the revised manuscript to emphasize surface snow bidirectional reflectance factor measurements. Reflectance factors are useful here, because by definition, they are comparison measurements to ideal Lambertian reflectors.

   Second, the manuscript overgeneralizes in making reference to previous snow SSA measurement methods. As a result, readers are to assume that the anticipated NERD instrument will be better and cheaper than previous methods. For this reason, we rewrote the entire manuscript to focus on our scientific results. We intend to present the NERD measurement method only in the context of monitoring snow surface BRFs to study how LAI affect snow

albedo feedbacks and snow metamorphism.
We cannot, at this time, give a full cost estimate for the production quality version of the NERD. We were able to create two functioning prototypes, which are not fully weather-proofed, insulated, or durable (although it has endured multiple flights, car trips, and field campaigns) for roughly 500USD.

3. *Particularly bothersome are some generalizations and omissions when discussing previously presented measurement methods and the motivation behind and the potential benefits of the NERD. Fast and nondestructive snow SSA measurements can be obtained with the InfraSnow (introduced by Gergely et al. 2014) or by contact spectroscopy (introduced by Painter et al. 2007), for example. No sampling is required, no samples are destroyed. In fact, the InfraSnow was developed for some of the same reasons and applications as the NERD, as stated by Gergely et al. (2014), and its presentation additionally included a quantitative uncertainty analysis and measurement validation, yet none of this is mentioned in this manuscript. Instead, all previously presented measurement methods for deriving snow SSA are falsely lumped together, and the manuscript gives the impression that the anticipated NERD method will be the first and only fast, nondestructive snow SSA measurement method, for example. This is poor 'scientific' work. The authors should either summarize and discuss the various measurement methods separately and in much more detail without overly generalizing and thus without making misleading and false claims, or they should simply state that they are attempting to develop a novel measurement tool that allows fast, nondestructive SSA measurements without suggesting that such measurements are not possible with (any of the) previously developed measurement methods. Also, NIR photography should be included as a reference in the list of currently available optical SSA measurement methods:*
@ARTICLE{Matzl+06,
author = {M. Matzl and M. Schneebeli},
title = {Measuring specific surface area of snow by near-infrared photography},
journal = jg,
year = {2006},
volume = {52},
pages = {558–564},
number = {179},
doi = {10.3189/172756506781828412}

   We added the missing references to the introduction. Furthermore, we provided more details regarding each instrument technique. In the revised manuscript, we keep these references concise to instead focus on the specific background information pertinent to the new purpose (i.e., snow metamorphism in the presence of LAIs).

4. *The main results in the context of the presentation of the NERD measurement method are summarized in Fig. 6. The effect of relevant sources of uncertainty should be discussed quantitatively instead of only stating the variability of the fitted exponential function for the extremely limited number of samples used to derive the fit (see point 1). Here, another effect is of interest: The small penetration depth of just a few mm or less at long NIR wavelengths is clearly much shallower than the penetration depth of visible light which forms the main contribution to overall solar irradiation. So, if snow surface SSA is measured at long NIR*

wavelengths, how realistic is it to analyze overall snow albedo based on the derived SSA value? It may be that the top few mm of the snow cover that determine long-wavelength NIR reflectance do not represent the full near-surface snow that determines overall snow albedo, e.g., a thin layer of surface hoar or some very small windblown snow fragments deposited at the very surface. Such a discussion would also add further scientific value to the study beyond presenting a novel SSA measurement method.

Thank you for bringing this interesting point regarding snow albedo to our attention. As mentioned, because the NERD only probes a thin surface layer of the snow, these measurements are not the best representation of snow albedo at large. Therefore, we removed language that implies that snow infrared BRFs are a good proxy for snow broadband albedo.

5. *Terminology: Throughout the manuscript, 'error' should be changed to 'uncertainty' or 'difference', depending on the context. Usage of 'error' when actually talking about 'uncertainty' or simple 'differences' is deprecated in measurement science and avoided to guarantee a more precise and meaningful terminology (see the 'Guide to the expression of uncertainty in measurement'), especially as a realistic assessment of uncertainties (and not errors) becomes increasingly important in remote sensing and climate modeling applications.*

   As recommended, we changed "error" to "uncertainty" or "difference" where appropriate throughout the revised manuscript.

6. *page 1 line 1: Is SSA an important physical property because it directly affects solar radiation, or is it important for another reason and it also affects solar radiation? The authors should specify this.*

   We removed this confusing sentence from the abstract.

7. *page 1 line 2f: This is a misleading generalization, if no further details are given about the various different SSA measurement methods (see point 3 above). The authors should remove this sentence and instead focus on the analysis and description of the NERD measurement principle in the abstract, and, e.g., on its possible future use to track snow SSA evolution on a time scale of hours.*

   We removed the misleading sentence and over-generalization regarding other snow SSA measurement methods. In the revised abstract, we focus on the NERD as a tool to monitor surface BRFs of snow with and without large LAI concentrations.

8. *page 1 line 17f: I do not understand this sentence. What is 'positive snow internal albedo feedback'? Is this the same as 'positive albedo feedback' in the previous sentence? This sentence could probably be rewritten to clarify.*

   We repurposed the introduction section. As a result, mention of snow internal albedo feedback is delayed until more specific background presented later in the introduction.

9. *p.2 l.4: What 'particles'? Snow is not a granular material of individual particles or grains but a material characterized by a complex 3D microstructure with continuous ice and air phases. Probably this should be the 'snow microstructure' or are the authors talking specifically about modeling snow here as a matrix of suspended ice particles?*

Thank you for pointing out a confusing part of our definition of snow SSA. We changed the wording around eq. 1 to apply to snow as a porous ice / air microstructure, instead of what it represents in particle based snow models.

10. *p.2. l.22: What is 'grain growth'? Snow is not a granular material. 'grain growth' could simply be left out. ... where solar heating induces a further decrease in SSA, ...*

    We removed this sentence.

11. *p. 3 l. 1 – 6: This is a misleading generalization (see point 3 above). Discuss different methods separately and in more detail, or simply state (1) that different methods to measure snow SSA for different applications have been presented previously (including the corresponding references) and (2) that this study describes a novel measurement method for fast and non-destructive SSA measurements (without trying to motivate it by making misleading and false claims about other measurement methods). Readers can then go back to the cited studies for details and see for themselves how different measurement methods compare to each other and what may be an advantage or disadvantage for different applications. Because a short and still adequate, i.e., not misleading or false, description of all relevant previously presented SSA measurement methods may be difficult to achieve within a few of lines of text, the following approach could be used: keep lines 1 – 3 and add reference Matzl and Schneebeli 2006 (see point 3 above), delete lines 4 – 6, keep line 6f and add: ... is widely sought after, which not all (or which only few) previously presented measurement methods allow. Here, we introduce ...*

    We removed the misleading generalizations and expanded on the discussion of the most relevant techniques. The restructured manuscript at large also relieves these previously fundamental flaws with the previous introduction.

12. *p. 4 l. 18 – 25: This is not a validation for determining BRFs of snow with the NERD due to the very different nature of snow (uneven surface, extensive volume-scattering). So, l. 24f would be more correctly rephrased as: ... to obtain BRFs on smooth reflectance standards with a measurement uncertainty of ..., or simply delete this statement.*

    Following this suggestion, we changed this sentence to include "...obtain BRFs on smooth reflectance standards.... (sec. 2.1, par. 4)"

13. *p. 4 l. 32: pixel (2D) or voxel (3D equivalent of pixel)?*

    Voxels for 3D reconstructions, pixel for 2D cross sections. We clarified this in the revised manuscript.

14. *p.4 l. 33f: Can the authors give the temperature of the CT and CT sample more accurately than below 0°C, if snow can't survive much more than 15 min? How does this affect snow SSA evolution during the duration of CT measurements? Has this CT been used for snow SSA measurements previously, is the CT resolution high enough to yield reliable snow SSA values, have previous CT measurements of snow with this CT been validated against other measurement methods (or other CT setups)? This information should be included in the text.*

    CT scans were conducted in a cold lab at roughly 27 degrees Fahrenheit. Snow SSA evolution over the course of 15 mins is assumed to be minimal, which is why we report the technical specifications of the CT in the text. Yes, the CT machine has been used for SSA measurements previously. We added a reference to Lieb-Lappen et al. (2017), who provide a thorough presentation of the CT methodology for ice samples. Here, we applied their methods to snow samples and calculated snow SSA according to Pizner and Schneebeli (2009), whom we also cite in the text. Based on the volume rendering images, which clearly show the finer scale features of the higher SSA needles, we believe that the resolution is high enough to derive reliable SSA, although we are unsure of the range of uncertainty that these algorithms yield. While the snow images in (previous) Fig. 3 can facilitate this assumption, we removed the images from the revised manuscript to streamline the main messages.

15. *p. 5 l. 10: Delete 'relatively'.*

    We folded, condensed, and rewrote the snow samples descriptions section. In the revised manuscript, we reclassify the samples according to Fierz et al. (2009). We also removed the word "relatively."

16. *p. 5 l. 20: What is 'highly sintered' snow. Old hard snow?*

    We now describe snow physical parameters according to Fierz et al. (2009). As a result, we removed this description.

17. *p. 6 l. 9: What is 'visibly apparent snow metamorphosis'? Is this temperature-gradient metamorphism or equal-temperature metamorphism or both, resulting in what type of snow (e.g., depth hoar or melt-freeze or other)? The authors should specify this in the text or simply list the physical properties of the snow sample and refer the reader to the CT images for further information.*

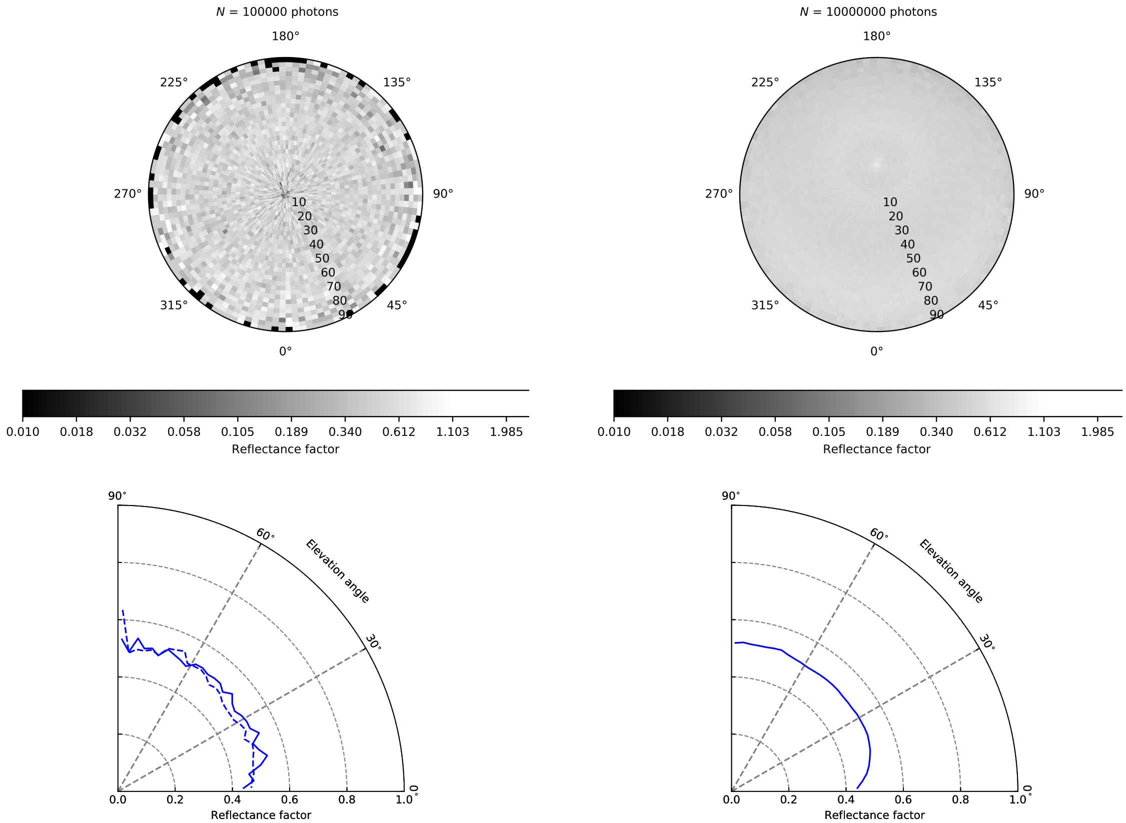
    Physical properties are now provided in Table 2 according to Fierz et al. (2009). We removed this confusing description.

18. *p. 6 l. 13ff: Has this Monte Carlo model been validated or at least used for snow previously? Is there any indication of what the expected uncertainty is for applying the model to snow (and not only to Lambertian surface scattering as described on p.7)? Such information should be included in the text, if it is available.*

    This Monte Carlo model is applied in a few previous studies to study light penetration in snow (e.g. Smith et al. (2018)). The model best approximates a very dense ice cloud with small suspended aspherical ice particles. Therefore, it is difficult to quantitatively estimate the uncertainty associated with its results applied to snow. Here, we apply the model to study directional reflectance. For validation, we provide comparisons with the SNICAR model for spheres. Albedo calculated for spheres agrees with that calculated with the SNICAR model. This comparison is provided in the text and data are shown in Fig. 3.

19. *p. 6 l. 23: Why are at least 100 thousand photons used per simulation, while commonly millions of photons are needed for complex Monte Carlo raytracing simulations. Have the authors checked that an increase in photons beyond the photon numbers that they have chosen does not lead to significant changes in the Monte Carlo modeling results for snow? If this is the case both for the tested Lambertian surfaces and for Monte Carlo simulations for volume-scattering snow, they should state this in the text. Or they should state how much a further increase in the number of photons may change the modeling results for snow.*

We did not clarify this previously in the text. In the revised manuscript we touch on this, but please see the below modeling results here for further information.



In the left column, we show BRFs calculated for snow from a simulation of 100,000 photons at 3x3 degree resolution. Azimuthally dependent BRFs are too noisy for meaningful interpretations. Azimuthal averaging (bottom row), reduces Monte Carlo noise, but not sufficiently for useful comparisons to NERD measurements.

In the right column, we show BRFs calculated for snow from a simulation of 10,000,000 photons (also at 3x3 degree resolution). Here, the specular reflection feature can be faintly seen (for an illumination zenith angle of 20 degrees). This is a good indication that Monte Carlo noise is sufficiently small. As expected, azimuthal averaging (bottom row) removes almost all Monte Carlo noise.

In the revised manuscript, all Monte Carlo BRFs presented are calculated from simulations of 1,000,000 photons and are azimuthally averaged. While azimuthally dependent results are great for data visualization, they do not provide any additional information, as azimuthal directional scattering is determined at random from a uniform probability density function ranging from 0 to 2π. Therefore, BRFs are azimuthally symmetric.

In further testing, we find that it is best use 10,000,000 photons to generate the figures shown above. With azimuthal averaging, however, BRFs stabilize for simulations of 250,000 to 500,000 photons. Therefore, in the revised manuscript, we show only results presented for simulations of 1,000,000 photons, which are sufficiently stable.

20. *p. 6 l. 24ff: Are the ice particle scattering properties obtained for randomly oriented or preferentially oriented ice particles (horizontally, vertically, something else?) within the*

snow matrix? How realistic is this assumption for the analyzed snow types? I would intuitively expect that random orientation should be the most realistic assumption in general, but some snow does show strong anisotropy. This information should be included in the manuscript. Similarly, are all ice particle types equally realistic representations of natural snow? Particularly hexagonal plates seem rather extreme when intuitively compared to the 3D microstructure of natural snow, which is also confirmed in Figs. 4 and 5. Maybe it would be more realistic not to include hexagonal plates in the analysis, which could also streamline the discussion?

The single scattering properties are obtained for randomly oriented ice particles. This is now clarified in the text. As mentioned previously, the model best represents a very dense ice cloud. It is not necessarily the best representation for snow, but its purposes are to (a) approximate the relationships between snow SSA and BRFs at 30 and 60 degrees viewing and (b) to explore how much variability we might expect for different snow types. While previous snow albedo models use idealized spherical particle surfaces, here, we are interested in exploring how BRFs change when we apply full scattering phase functions from aspherical ice particles.
The hexagonal plates yield consistently lower BRFs due to their (even more) extreme forward scattering peaks. In response to this comment, we removed the plates from the results and discussion.

21. *p. 6 l. 29f: Delete this sentence, it is a duplicate of l. 22f.*

    Thank you for pointing out this editing oversight. We removed both of these sentences in the revised manuscript.

22. *p. 7 l. 14ff: How are the stark differences in CT and NERD measurement volumes included in the analysis? How does this affect the analysis results (see also point 1 above)? This should be discussed in the text.*

    This comment highlights one of our main concerns with our calibration approach, and could potentially be one of the main sources of uncertainty regarding the precise determination of snow SSA using the NERD. We touched on this point in our response to point 1 above. In short, we attempt to mitigate these uncertainties by sampling just the uppermost layers of the snow pack. To highlight this approach we changed the title of the manuscript to include "surface."

23. *p. 7 l. 24: How can this be claimed without validating snow BRF measurements with the NERD against any other independent snow BRF measurements, e.g., a gonioreflectometer, and without providing any quantification of the term 'relatively accurate' when comparing NERD BRF measurements and modeled BRFs? The authors should either delete this sentence or provide a detailed quantification instead of a vague statement.*

    We rewrote the results and discussion section. Therefore, this comment is only generally relevant, but still important. In theory, a gonioreflectometer would be subject to the same sources of bidirectional reflectance measurement uncertainty in the case of extensive volume scattering. Because we expect extensive volume scattering to be minimal at wavelengths of interest (see also response to comment #1), we believe the NERD gives accurate BRF measurements, which are directly compared to Lambertian reflectance targets in frequent calibration.

24. *p. 8 l. 10f: Better: With the InfraSnow, Gergely et al. (2014) were able to determine the reflectance values of nominal 25 %, 50 %, and 99 % reflectance standards to within an accuracy of better than 1 %.*

    Due to our repurposing, this comparison is less relevant to the revised manuscript results and discussion. Therefore, we removed it.

25. *p.8 l. 11: 'directional-hemispherical reflectance' is not correct here due to the diffusing cone in the InfraSnow that prevents direct illumination of the snow surface and instead guarantees predominantly diffuse illumination. 'directional-' should be removed.*

    Thank you for pointing out the incorrect description of reflectance measurements conducted by the Infrasnow. We corrected this description in the introduction and removed this discussion from this section.

26. *p. 8 l. 12 – 16: Best to remove these two sentences. Lambertian reflectance standards are only part of the testing performed for the InfraSnow. Additionally, various other surfaces, including snow, are tested. This should be included if l.12,13 are kept in the text. The second sentence does not add important information and is highly speculative, especially when trying to translate the results found for reflectance standards to reflectance measurements on snow, due to the very different nature of NIR light scattering in snow and the differences in the applied measurement techniques (see also point 1 above).*

    We removed these sentences.

27. *p. 8 l. 28ff: How does this BRF uncertainty affect the derived snow SSA? And how could light leakage to and from the outside of the NERD due to an uneven snow surface or due to specular reflections also add to the uncertainty in BRF measurements (see also point 1 above)?*

    BRF uncertainties will propagate through to SSA calculations. These uncertainties are included in the error bars in NERD SSA results in figs. 6 and 7. Light leakage into the dome saturates the photodiode sensors, making measurements in diffuse lighting conditions difficult this point is discussed further in the text.
    Also, because dark currents are subtracted from photodiode currents every measurement cycle, static ambient light leakage into the dome corrected for in BRF calculations. In fast-changing ambient lighting conditions, measurements are not reliable (see also response to point 1 above).

28. *p. 8 l. 32ff: The authors should indicate which Figure or Table they are referring to.*

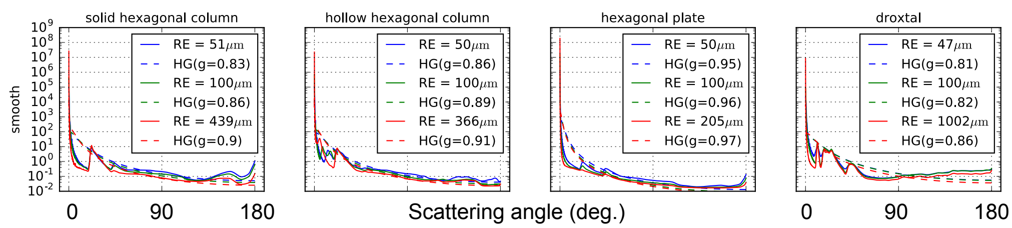
    The presentation of these results are now within section 3.1, with appropriate reference to data plotted in Fig. 3.

29. *p.9 l. 1f: What is an estimate of this uncertainty then? Can the authors provide a quantification? Otherwise, it is better not to include such statements.*

    We removed this sentence.

30. *p.10 l.3 – 18: I do not see the immediate relevance of this discussion. This could be mostly removed to streamline the manuscript and focus on more crucial results, which are given in the next paragraph. I would prefer to see the authors try to include an actual quantitative uncertainty assessment of their measurement method, including the effect of grain shape on their modeling results instead of this ancillary discussion.*

    While these results and discussion are not directly relevant to the NERD snow SSA calibration at 1.30 μm, we include them in the manuscript because they are interesting, surprising results. In response to this comment, we trimmed this discussion.
    As pointed out, different grain shapes have an effect on the Monte Carlo calculated snow albedo and BRFs. The spread in these calculations is plotted in Figs. 3 and 4. We speculate that these variations across shape habits are directly related to the variations in the particles' asymmetry parameters.



    Droxtals have the lowest asymmetry parameters while hexagonal plates have the highest. It is difficult to determine why the simulated BRFs are larger at 30 degrees (zenith) than at 60 degrees. We speculate that the combination of backscatter and more scattering at 30 degrees than at 60 degrees, according to the phase functions, are partially responsible for the different BRFs at 30 versus 60 degrees. Confirming these speculations would require more Monte Carlo testing and further investigation.
    While we are unable to reach a conclusion regarding these concerns, we added reference to Kaempfer et al. (2007) who also show larger reflectance factors at 30 degrees than at 60 degrees (viewing) (for $\lambda = 900$ nm).

31. *p. 10 l. 22: I do not see a compelling reason in the presented data why this relationship has to be an exponential function. Could it be something else (linear relationship), and would this significantly change any of the results? If so, this effect should be included in the SSA measurement uncertainty. Also, what does a constant SSA measurement uncertainty across the entire SSA range mean for using the NERD to measure different snow types? High relative SSA measurement uncertainty for snow characterized by low SSA (what snow types are those?) and low relative SSA measurement uncertainty for snow characterized by high SSA (what snow types are those?). This should be added to the text to illustrate the uncertainty in the derived BRF-to-SSA relationship beyond the mere presentation of the values for the root mean square differences.*

    These are good discussion points that would improve the presentation of the NERD as an accurate snow SSA instrument. Unfortunately, we do not have enough measurement data yet to fully address these comments. As a result, we changed the focus of the revised manuscript to focus on our key scientific results pertaining to snow metamorphism with and without added LAIs.

32. *p. 11 l. 9: Delete 'accurate'. There is no quantitative validation of the SSA measurements in the manuscript. 'quick, reliable, and repeatable' convey the full picture. Even 'repeatable' could be removed because it is implied by 'reliable'.*

    We removed "accurate" and "reliable" from this sentence.

33. *p. 11 l. 16,17,18: The authors should replace 'will' with 'can' or 'could' or 'may', or preface each of these statements by 'We believe that ....' or 'We intend to use the NERD for ...' or 'The analysis indicates the potential for ....' or similar. Selling such statements as foregone conclusions seems like a far stretch given the limited analysis in the manuscript and the inherent uncertainty of future developments (see also point 1 above).*

    We revised this section to provide conclusive statements in the context of the NERDs limitations. We also suggest further validation to better justify the NERD as a tool to accurately monitor snow SSA.

34. *Caption Figure 3: Snow is not a granular material. Better: ... 'as the snow microstructure gets coarser' or 'is characterized by more rounded shapes'.*

    We removed this figure from the revised manuscript.

We are also grateful for Anonymous Reviewer #2's review, as it has helped develop a better presentation of our study. Like Anonymous Reviewer #3, Reviewer #2 also pointed out an inappropriate use of language and recommended a major revision. We agree with this recommendation and revised, reorganized, and rewrote much of the manuscript accordingly.

In the revised manuscript, the new main focus of how LAIs affect snow metamorphism relieves the need for a lengthy background discussion on the state of the art snow SSA measurement methods. Instead, we present background information in the introduction pertinent to understanding how LAI can possibly affect snow albedo feedbacks. Additionally, we removed technical details from the methods section unrelated to the results and discussion. A condensed presentation of these details is now contained in the appendix. Finally, the reorganized the results and discussion section into two main subsections. First, we present results from our NERD BRF to SSA calibration study, including those from Monte Carlo modeling. Second, we introduce new results from LAI in snow experiments using the NERD to observe snow metamorphism. Because we removed language that implies that the NERD is validated for precise snow SSA retrieval, we emphasize approximate SSA results are enough to observe the significant difference in snow surface behavior in experimental snow with added LAI versus natural snow. The revised discussion therefore focuses on the NERD and our experimental results specific to this study, relieving the need for a lengthy discussion on the advantages and disadvantages compared to state of the art snow SSA measurement methods.

Following are our responses to Reviewer #2's comments, which we italicize for reference:

1. *p.1, L17-18: "Positive snow internal albedo feedback occurs due to the strong dependence of snow infrared reflectance on snow specific surface area (SSA)." This sentence is too compact. Please explain this internal albedo feedback more explicitly.*

    We rewrote the introduction section. As a result, the mention of snow internal albedo feedback is delayed until later in the introduction, where we describe this more specifically in the context of our revised manuscript.

2. *P1., L18-20: "The Snow, Ice, and ... in Fig. 1". Fig 1 is not sufficiently justified here. It should be moved later in the paper, when describing the reason for the selection of the wavelengths 1300 and 1550 nm for the detection of SSA.*

   Thank you for this suggestion. We moved mention of these basic SNICAR modeling results to the methods section, where we describe the motivation for selecting 1300 and 1550 nm.

3. *p.2, L9: "...are equivalent for convex bodies (see Appendix A)." There is no need to write an appendix to make a geometrical demonstration that was already derived more than 150 years ago. Instead, please refer to some book of convex geometry, or better to the original demonstration by Cauchy (as done in Pirazzini et al.: "Measurements and modeling of snow particle size and shortwave infrared albedo over a melting Antarctic ice sheet", The Cryosphere, 9, 2357-2381, `https://doi.org/10.5194/tc-9-2357-2015`, 2015).*

   We removed this appendix. The lone appendix now contains specific details regarding the NERD that we removed from the methods section in response to below comments.

4. *p.2, L16-17: "observe seasonal scale snow albedo decline in springtime Colorado". Could you please improve the expression, for instance as "observe snow albedo decline during the spring season in Colorado"?*

   We removed the paragraph containing this sentence.

5. *p.2, L17: "In contrast, however, they find that snow albedo is primarily related to dust concentration." This sentence is incorrect. First of all, the snow albedo is mostly determined by the optical properties of the snow, and not by dust concentration. You may want to say that it is affected by dust concentration, but you cannot claim that it is the main albedo driver. Secondly, why you wrote "In contrast"? In the paper by Skiles and Painter (2017) the springtime albedo decline was accelerated by the dust load, which concentrated at the surface during the progress of the melting further decreasing the albedo. Hence, the increase in dust concentration at the surface affected the observed albedo decline, and was not in contrast with it.*

   Thank you for pointing out the confusing style of this sentence. Because this entire paragraph was worded poorly, we removed it from the revised manuscript. In the revised manuscript, general background information regarding how LAIs directly affect snow albedo is rewritten and presented in the first paragraph.

6. *p.2, L19: "where the albedo reduction..." Instead of "where" I suppose you meant something like "who showed that...", right?*

   We removed this sentence and relocated the relevant citation to paragraph one (see also above response).

7. *p.2, L21: "snow internal albedo feedback" shouldn't be "internal snow albedo feedback"? As pointed out in my comment above, it is not at all clear what you mean for "internal" snow albedo feedback. Please explain.*

   We removed the mention of snow "internal" albedo feedback in the introduction. In the revised manuscript, we relocate this topic to the discussion section where we further describe this snow metamorphism based feedback, where the decrease of snow SSA enhances absorbed infrared radiation which contributes positively to additional snow melt.

8. *p.2, L23-24: "Surface warming can also reduce snow grain growth rates, however, if growth processes from vapor diffusion and strong temperature gradients are affected negatively (Flanner and Zender, 2006)." The meaning of this sentence is very obscure. Could you explain more clearly what you mean, without requiring from the reader to study Flenner and Zender in order to understand what you mean?*

   We thoroughly revised the introduction. To this end, we clarified temperature gradient metamorphism in the context of this study.

9. *p.2, L25-31: "Recent studies ..." This section seems to be out of context: it is not linked to the purpose of the paper. Please remove it, or explicitly explain the connection with the content of the paper.*

   We reworded this section in the context of the revised manuscript's main purpose. We agree that this section was originally out of context, but in the revised manuscript, it is directly relevant to the main results and discussion.

10. *p.3, L16: "The NERD is designed to measure 1.30 and 1.55 µm BRFs". Please explain here why these wavelengths were selected, and highlight here the analogy with DUFISSS in the wavelength selection.*

    We changed the first two paragraphs of section 2.2 to one, explain why these wavelengths were selected, and two to compare the method to the DUFISSS. Accordingly, Fig. 1 is now referred to here to demonstrate the utility of 1.30 and 1.55 µm reflectance measurements in determining snow (with LAIs) grain size. Paragraph two starts by describing the analogy with DUFISSS before stating the NERD technical description.

11. *p.3, L25: "The NERD is similar to that of ... in that it uses ...." Please reformulate the sentence improving the linguistic expression and moving it above (see previous comment).*

    We revised the sentence. It now reads "The design principle is similar to the...." "and The NERD also uses.... (sec. 2.1, par. 2)"

12. *p.3, L27-30: "LEDs are toggled ... (20% duty cycle)" A lot of not needed technical details. Please remove.*

    We removed these details.

13. *p.3, L31-32: "Here, rather, we direct photodiodes toward the illuminated surface in a black dome to measure BRFs" The linguistic expression is particularly poor in this sentence. Instead of "we" use a passive expression.*

    We removed this sentence. Furthermore, the methods section in the revised manuscript is more consistent in the use of passive voice.

14. *p.4, Sect 2.1 and 2.2. Please remove all the technical details that do not provide any added value to the interpretation of the measurements. E.g. "Waiting 0.75 seconds after toggling the LED allows for enough time for the photodiode current to stabilize. After these currents*

stabilize, 100 voltage samples (ranging from 0.1 to 1.0 Volts) are then rapidly collected using the Ruggeduino-ET's ADCs. The average voltage obtained during active illumination is differenced from the average dark current voltage to derive reflectance 10 factors.", "The reflectance of the targets are measured with high precision across a broad spectrum. At 1.30 (1.55) µm, the white and gray targets have calibrated reflectances of 0.95073 (0.94426) and 0.42170 (0.41343), respectively, as reported by the manufacturer.", "Small samples of snow are collected in roughly 10 cm tall cylindrical plastic sample holders and placed into the machine. An X-ray source is emitted at 40-45 kV and 177-200 micro-Amps. X-ray transmittance is measured as the machine rotates the sample. Setting the exposure time to 340 ms at a pixel resolution of 14.9 µm with rotation steps at 0.3-0.4 degrees allow for fast scan times of roughly 15 minutes. These short scan times are necessary to complete the scan without too much absorbed radiation melting the snow."

We removed these technical details. We also repurposed the appendix to contain details only relevant to the operation of the instrument. In the revised manuscript, section 2.1 contains details only relevant to the results and discussion and not to preliminary instrument results obtained in testing.

15. *p.4, L19: "Using both…" What do you mean for "both"?*

    We meant "two," but reworded this sentence to mitigate confusion.

16. *p.5, Sect 2.3. This section needs to be rewritten in a much more compact and consistent way. Expressions such as "oldest class" are meaningless. You should really apply the snow descriptors listed in The International Classification for Seasonal Snow on the Ground (Fierz, 2009). Instead of repeating 6 times that the measurements were performed in Hanover and samples were transported to CRREL for X-ray microTomography, focus on the characteristics of the different samples. Eliminate subparagraphs and unnecessary details such as "…distinguishable only by the container they were stored in…", or the sentences in lines 24-27 (until "…nearby lab for X-CT analysis"), and the not relevant sentence "All samples with added LAI included in the NERD SSA calibration dataset were first screened to remove samples with heavy LAI loads that caused direct snow darkening at 1.30 5 and 1.55 µm."*

    We followed these suggestions and revised the methods section accordingly. These descriptions are now condensed and summarized in Table 2. We classified snow samples according to Fierz et al. (2009). Furthermore, we applied their convention to data plotted in Figs. 4 and 5 so that colors, key codes and symbols conform (as closely as possible) to their snow classification descriptors.

17. *p.6, Sect. 2.4. You need to provide some introduction explaining the purpose of the model simulations*

    The purpose of the Monte Carlo simulations is to study light emission by the NERD and the resulting scattering within idealized snow packs. This is now stated at the beginning of section 2.3.

18. *p.6, L30: replace "multiple" with "BRFs"*

    We removed this sentence.

19. *p.7, L24 and following: this sections need to be moved after the thorough presentation of the results.*

    We rewrote the entire results and discussion section. To this end, we moved all NERD Lambertian test results and analysis to the end of the NERD specific subsection in presented within section 2.

20. *p.8, L12-13: "Both instruments make use of Lambertian reflectance standards for calibration and testing." This is a repetition: you have already explained in the lines above. Please remove it. Instead of discussing the opportunity of using reflectance standards to calibrate SSA detector based on active optical sensors, you could focus the discussion on comparing the different working principles, and strengths/weaknesses of the devices.*

    We removed this sentence and instead focus discussion on snow SSA calibration.

21. *p.8, L13-16: "Although each instrument..." This sentence is a rather obvious statement that does not add anything to the paper. Please remove.*

    We removed this sentence.

22. *p.8, L23: "Although photodiode responsivity varies with temperature, frequent calibration minimizes these errors" This is a critical point that deserves further explanation. Is calibration required on the field before/after each measurement (as done for instance when using the IceCube device)? If this is the case, please explain, and describe the needed measurement procedure, including calibration.*

    Yes, (frequent) calibration is required (preferred) in the field to correct for temperature effects that change photodiode and LED performance. These are more technical points that we removed in the revised manuscript to focus on more relevant experimental procedures. We could, however, provide further discussion in an appendix.

23. *p.8, L34 – p.9, L1: "Monte Carlo simulations predict lower BRF values at 60 degrees than at 30 degrees". This sentence refers to radiances at 1.30μm: looking at Fig. 4 I see the opposite, i.e. that for most grain shapes, when SSA is larger than 40 m^2kg^{-1} BRF is larger at 60 degrees than at 30 degrees.*

    Monte Carlo BRFs (line segments) are higher at 30 degrees viewing than at 60 degrees viewing. Oppositely, NERD BRFs are higher at 60 degrees viewing than at 30 degrees viewing. These are important results that we elucidate in the revised results and discussion.

24. *p.9, L17: "Hemispherical reflectance measurements theoretically reduce measurement variations associated with grain shapes". Why? Please explain. Comparing Fig. 4 (top) and Fig. 5 (top) where, respectively, BRFs and directional-hemispherical albedo are illustrated, I would say that both hemispherical and directional measurements show a very similar dependence on grain shape. In my opinion, Fig. 4 would deserve a much deeper analysis. For instance, why the BRFs measured with NERD are so much higher than the model results in 1.30 μm at 60 degrees? And why the modeled BRFs at 1.30 μm are lower at 60deg than at 30 deg? Etc...*

    We clarified comparisons of Monte Carlo modeling to the NERD measurements and removed the confusing sentence quoted above.

25. *p.9, L31-32: "These large variations in reflectance across grain shape are the largest source of uncertainty in snow SSA measurements using infrared reflectance." I disagree. Even larger uncertainties can be associated to the instrument set up in certain snow conditions. You have not discusses the effect of natural light entering into the dome and detected by the photodetectors. Probably, you will have this unwanted light source every time the target snow surface is not perfectly smooth, unless you insert the edges of the dome for several millimeters inside the snow surface. With other optical-based devices to derive SSA (such as DUFISSS and IceCube), a large source of uncertainty may derive from the snow sampling procedure (especially in case of surface hoar or very soft new snow). In my opinion, even your Fig. 4 shows that the large scatter in the optically derived SSA is not only attributable to a grain shape effect. The instrumental and set up error sources deserve much more discussion.*

    We removed this sentence. Light entering the dome is subtracted out from background light measurements during each measurement cycle (see also comment # 27 from referee #3).

26. *p.10, L16-17: "These calculations confirm this hypothesis, as 1.55 µm narrow band albedo with a full width at half maximums of 0.26 µm (doubled from 0.13 µm) closely agree with NERD BRF measurements." Please show these results in a Figure.*

    We now show these results in Fig. 3 (right).

27. *Figure 2: A much clearer photo of the sensor is needed, which would show only the essential components. The text in the figure should be less technical, or the technical terminology should be explained (what is the meaning of "LCD"? Is the whole sentence "LCD provides … data collection" needed? If yes, you should better explain its content, possibly in the main text and not in the figure. Is the diagram of the Transimpedance amplifier circuit needed? Instead of providing so many technical details, you should explain what the achieved performance is and why it is needed. Also the meaning and scope of the sentence "Using feedback resistances as low as …" in the figure caption is totally obscure. What is the scientific message behind it?*

    We removed the circuit diagram and replaced it with a clear photo of the underside of the NERD, which includes the mounted LEDs and photodiodes.

28. *Figure 4: Please mark the vertical and horizontal grids, to facilitate the comparison among the plots.*

    We added gridlines to this figure.

29. *Figure 5: what is the added value of this figure? The considerations on the effect of grain shape drown on the basis of directional-hemispherical albedo calculation can equally well been drown on the basis of Fig 4 (showing BRF calculations). I would simply remove the figure.*

    We agree that this Figure is slightly redundant. The purpose of the revised figure (now Fig. 3) is twofold: one (left), to compare Monte Carlo albedo calculations directly with SNICAR modeling for snow validation; and two (right), to show how widening the half-widths in these models supports our hypothesize for why measured BRFs at 1.55 μm are higher than expected (see also comment #26 above).

30. *Table 1: in the table caption please explain the meaning of the used symbols and the content of each column and row.*

    We reformatted Table 1 and added symbolic descriptions in the caption.

Finally, we appreciate Dr. Dumont's comments and adhered to their recommendation. We respond to their comments below as done previously:

1. *The introduction is in my opinion, a bit too scattered and confusing and some literature references are also missing. More specifically,*

   (a) *it's a bit weird to have references to calculation in an appendix in the introduction. For me, either the calculation already exists in the literature and then it would be nice to add the reference or it's a new result that should be included in the results section*

   We removed this appendix and moved the reference to Vouk (1948) into the introduction.

   (b) *page 2, lines 22-31 , I don't think it's necessary to go into too much details about the SSA evolution in time, a few sentences without any equation should be sufficient. It's not directly related to the objective of the paper and would give more space for discussing the sate of the art of SSA measurements*

   While these details were irrelevant to the original manuscript, because the main purpose of the revised manuscript is to study how LAIs affect snow albedo feedbacks related to snow metamorphism, this background information is now relevant. We rewrote the introduction accordingly.

   (c) *page 3, lines 1-8, this section is really important for the rest of the paper. It seems to me that it would worth more details on the methods (advantages and drawbacks) and accuracy. Several methodologies are missing here such as IR photography (Matzl and Schneebeli, 2006) , SMP (Proksch et al. 2015) , and retrieval from spectral albedo which is also non destructive (Picard et al., 2016 , Dumont et al., 2017). Regarding SSA calculation from X-ray imaging, I think adding some discussion also on the methodology and resolution issue would be nice (e.g. Hagenmuller et al., 2016).*

   Because we restructured the manuscript to focus on how LAIs affect snow metamorphism, we do not go into too much detail about previous snow SSA measurement techniques. In the revised introduction, we expand on the discussion of only methods directly relevant to this study.

   (d) *Since you also present a Monte-Carlo model, maybe a short state of the art of existing theory and models to simulation snow BRF need to be added and why a new Monte-Carlo model is required ? e.g. Malinka, 2014 , Kokhanovsky and Zege, 2004 , Xi et al., 2006 ....*

   This is a good suggestion, however, we are unsure how to introduce this section into the revised manuscript at this time.

2. *Section 2.1. Some details are missing here (but maybe I did not check carefully enough), what is the diameter of the illumination ? How homogeneous is it ? What is the FOV of the photodiode ? In which azimuthal planes are they with respect to the illumination ?*

   We estimate the diameters of the illumination to be 1.5 and 3 cm and added these details to paragraph two of section 2.1. We gathered these details from the manufacture specifications documents which also indicate that the emission patterns are nearly isotropic.
   In testing, we detected direct light incident on the photodiodes from the LEDs by observing photodiode current responses when titling the dome upward in a dark room. These tests indicate that both the light emission patterns and the photodiode fields of view are not ideally isotropic and limited to a narrow cone in the forward direction. We eliminated this error source by mounting obstructions in the dome. These obstructions block the direct paths' from LEDs to photodiodes which eliminate the relevant photodiode response.
   The exact field of view of the photodiodes is difficult to determine. In the most accurate case, the photodiodes would view a greater surface area than that illuminated by the LEDs. This would ensure that the photodiodes are able to collect most light reflected from subsurface scattering. In the least accurate case, the photodiodes would view a very small surface area of the surface. In this case, while accurate BRFs would still be measurable on surfaces with minimal subsurface scattering, volume scattering would lead to errors in the measured reflectance factors.
   Our laboratory testing leads us to believe that the photodiode field of view yields a detectable surface area larger than that illuminated by the LEDs. This enables accurate snow BRF measurements. Because the emission patterns of the LEDs is not ideal, however, there are inevitably imperfections in the BRF measurement. These non-ideal effects are a source of BRF measurement uncertainty.
   For more specific details regarding the LEDs and photodiodes, please see the technical documents available from Marktech Optoelectronics: MTE1300N MT51550-IR MTPD1346-100.

3. *Page 7, Equation 5. Here I probably misunderstood something, why is the BRF averaged over all azimuths while the measurement is done only in two azimuthal planes ?*

   Modeled BRFs are averaged over all azimuths to reduce Monte Carlo noise and because we expect BRFs to be symmetrical in the azimuthal dimension. This is due to the uniform probability density function for which scattering azimuth angles are randomly generated. Please also see our response to Referee #3's comment # 19.

4. *Section 3, I think it would be less confusing for the reader to start with the model evaluation first.*

   We moved the Monte Carlo evaluation to the very beginning of section 3.

5. *Section 3.1. The section is long and a bit confused, can it be re-arranged ?*

   Yes. We re-arranged and rewrote all of the results and discussion section.

6. *Section 3.3, comparison with SNICAR should in my mind be part of the model evaluation. It's a bit confusing to have it mixed with the calibration.*

We moved the SNICAR comparison to the model evaluation section presented at the beginning of section 3.

7. *In the discussion, I would also add some details on the surface roughness effects and liquid water effect maybe (e.g. Gallet et al., 2014)*

8. *To my mind, both the conclusions and the abstracts should more clearly state the advantages and drawbacks of this new instrument compared to existing ones. The estimated accuracy in the SSA measurements should also be stated in the abstract.*

   We rewrote both the abstract and conclusions. They now include the NERD SSA uncertainty margin (10 m^2kg^{-1}) and brief discussion of the utility of the instrument in the context of the main limitations.

9. *Page 3, line 32, "flat black paint", it would be super interesting to know the spectrum, flat in which range ? I think these details are important for the discussions in the end of the paper.*

   We do not know the spectral characteristics of the flat black paint. We did, however, paint an experimental surface and measured very low BRFs at 1.30 and 1.55 μm, confirming that it is highly absorptive at these wavelengths.

10. *Section 2.2. An accuracy assessment of the SSA calculation from the X-ray images would be nice. I think 14,6 microns is quite rough for snow types of snow (e.g. e and a in Fig. 3).*

    Unfortunately, we do not present these uncertainties here. We did, however, add a reference to Lieb-Lappen et al. (2017) who provide a thorough analysis of the micro-CT procedure. Multiple samples for a given snow type (needles) provide an estimate of this uncertainty. These are indicated by the horizontal error bars in Fig. 4. For needles, this margin of uncertainty appears to be $+/-$ 10 m^2kg^{-1}.

11. *Section 2.3 Maybe a table would be clearer than a text description.*

    We summarized this section in Table 2 of the revised manuscript and included a physical classification in response to Referee #2's comments.

12. *Page 6 line 19 scatter →scattering*

    We changed "scatter" to "scattering."

13. *Page 6 line 20. After how many scatter do you stop following the photon ?*

    We do not terminate photons until they are absorbed or exit the snow medium. This is computationally possible at these relatively long NIR wavelengths, but such a scattering events cut off is necessary for simulating shorter wavelengths less than roughly 700 nm.

14. *Page 10 - last section, Picard et al., 2016 and Dumont et al., 2017 provide a detail assessment of the SSA retrieval uncertainties.*

15. *Page 11 – lines 3-7, this should be also indicated in the introduction.*

    We indicate this in the revised introduction.

~~Measuring~~ Monitoring of Snow ~~Specific~~ Surface ~~Area with 1.30 and 1.55 μm~~ Near-Infrared Bidirectional Reflectance Factors with Added Light Absorbing Impurities

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Abstract. Snow ~~specific surface area (SSA) is an important physical property that directly affects solar absorption of snow cover. Instrumentation to measure snow SSA is commercially available for purchase, but these instruments are costly and/or remove and destroy snow samples during data collection. To obtain rapid, repeatable, and in situ surface snow SSA measurements, we mounted infrared light emitting diodes and photodiode detectors into a 17 cm diameter black styrene dome. By flashing light emitting diodes and measuring photodiode currents, we obtain accurate 1.30 and 1.55 micron~~ albedo can range from 0.3 to 0.9 depending on microphysical properties and light absorbing impurity (LAI) concentrations. Beyond the widely observed direct and visibly apparent effect of darkening snow, it is still unclear how LAI influence snow albedo feedbacks. To investigate the LAI indirect effect on snow albedo feedbacks, we developed and calibrated the Near-Infrared Emitting and Reflectance-Monitoring Dome (NERD) and monitored bidirectional reflectance factors (BRFs) ~~. We compare measured snow BRFs with X-ray micro computed tomography scans and Monte Carlo photon modeling to relate BRFs~~ hourly after depositing dust and black carbon (BC) particles onto experimental snow surfaces. After comparing snow infrared BRFs to snow SSA, we found that both measured and modeled snow infrared BRFs are correlated with snow SSA. These ~~comparisons show an exponential relationship between snow 1.30 micron BRFs and SSA from which we calculate calibration functions to approximate snow~~results, however, demonstrate a considerable uncertainty of $+/-$ 10 m^2kg^{-1} in the determination of snow SSA from BRF measurements. After adding large amounts of dust and BC to snow, we found more rapid decreasing of snow BRFs and SSA in snow with added LAI compared to natural (clean) snow, but only during clear sky conditions. These findings suggest that the deposition of LAIs onto snow can enhance snow metamorphism from direct solar irradiance via net positive snow albedo feedback. The nondestructive technique for snow SSA retrieval presented here can be further developed for science applications that require rapid in situ snow SSA measurements. ~~The techniques developed here enable rapid retrieval of snow SSA by a new instrument called the Near-Infrared Emitting and Reflectance-Monitoring Dome (NERD).~~

1 Introduction

~~Earth's surface albedo is a primary component of the planetary energy budget. Of the vast natural surface types that determine Earth's fundamental radiative properties, snow cover is the most reflective. Fresh snow cover is especially reflective in the visible and less so in the near-infrared spectra, reflecting as much as 90 percent of the direct solar irradiance into the upward facing hemisphere. Snow cover is also a highly dynamic, unstable surface type in the Earth system . Changes in snow albedo, for example, drive positive albedo feedback and other nonlinear processes that can~~ Common light absorbing impurities (LAI) in snow include elemental (black) carbon (BC), brown carbon, and dust particulate matter, all of which play an important role in the climate system (Bond et al., 2013; Qian et al., 2015). In particular, these LAI at the snow surface can reduce snow albedo and enhance snow melt ~~and surface temperature anomalies (Fletcher et al., 2012; Qu and Hall, 2007; Winton, 2006; Hall, 2004) . Positive snow internal albedo feedback occurs due to the strong dependence of snow infrared reflectance on snow specific surface area (SSA). The~~ via the snow albedo feedback (Qu and Hall, 2007; Skiles and Painter, 2017). Hadley and Kirchstetter (2012) experimentally verify this effect and confirm what Warren and Wiscombe (1980) and the widely used Snow, Ice, and Aerosol Radiation (SNICAR) model ~~(Flanner et al., 2007) demonstrates this dependence and is applied here to simulate the spectral black-sky albedo of nadir illuminated snow in Fig. 1.~~

~~Snow SSA is defined as the total ice surface area to mass ratio, such that~~

$$\mathrm{SSA} = S/M = \frac{S}{\rho_{ice} V},$$

~~where S is the total surface area of a mass M of snow occupying an ice volume V and ρ_{ice} is the density of ice (917 kg m^{-3}) (Legagneux et al., 2002; Gallet et al., 2009). Previous studies demonstrate the strong dependence of snow infrared reflectance on snow SSA (Domine et al., 2006; Gallet et al., 2009). Modeling studies, such as~~ (Flanner et al., 2007, 2009) predict in that snow albedo reduction by BC is enhanced for larger snow effective radii. Numerical snow albedo studies, including those from Wiscombe and Warren (1980)~~and Flanner et al. (2007), also demonstrate this strong dependence using sphere effective radius as an optical metric for~~ , and Picard et al. (2009), typically model snowpack as a semi-infinite medium of suspended spherical ice particles. These models are highly accurate for spectral snow albedo calculations when the snow effective radius is a tunable parameter. Spherical snow ~~grain size. Gallet et al. (2009) also quantify snow SSA by its sphere effective radius (r_{eff}), defined by the radius of a sphere having the same surface area to volume ratio as the particles, such that~~

$$\mathrm{SSA} = \frac{3}{\rho_{ice} r_{eff}}.$$

~~Other studies quantify snow~~ grain size ~~by its sphere effective radius(RE) as it relates to the projected area of a particle, so that~~

$$\mathrm{RE} = \frac{3}{4}(V/A),$$

~~where A is the particle projected area (Jin et al., 2008). These expressions~~ is related to specific surface area (SSA) by its effective radius, such that SSA = 3/(ρ_{ice}Re). Expressions of sphere effective radii, r_{eff} and ~~RE~~Re, defined by ice particle surface area S versus ice particle projected area A, respectively, are equivalent for convex bodies ~~(see Appendix A)~~(Vouk, 1948) .

~~As surface temperatures increase, snow albedo generally decreases as snow SSA decreases. Recent studies verify this process of natural snow metamorphosis on seasonal timescales in Antarctica (Libois et al., 2015), New Hampshire (Adolph et al., 2017) , and Colorado (Skiles and Painter, 2017). Libois et al. (2015) find that SSA evolution occurs slowly in the extremely cold Antarctic environment. Adolph et al. (2017) monitor the evolution of snow albedo across three winter seasons in New Hampshire to determine a strong dependence of snow broad-band albedo on optically derived snow grain size (r_{eff}). These observational studies inform us on snow albedo measurements conducted on clean snow, with small concentrations of light absorbing impurities (LAI) such as dust and black carbon (BC) . Skiles and Painter (2017) observe seasonal scale snow albedo decline in springtime Colorado. In contrast, however, they find that snow albedo is primarily related to dust concentration. LAI can directly reduce snow albedo, but also indirectly darkens snow during metamorphosis. This indirect effect is demonstrated by Hadley and Kirchstetter (2012), where the albedo reduction due to the presence of BC in snow is amplified in snow of lower SSA . This enhancement of snow albedo reduction is another source of instability in the snow pack that increases the strength of snow internal albedo feedback.~~

~~When snow SSA decreases, a positive albedo feedback can exist where solar heating induces grain growth, further decreases SSA, and causes the snow surface to absorb additional solar radiation. Surface warming can also reduce snow grain growth rates, however, if growth processes from vapor diffusion and strong temperature gradients are affected negatively (Flanner and Zender, 2006 . Recent studies use~~ Snow SSA is defined as the total ice-air interfacial surface area S to ice mass m ratio, expressed in terms of its total ice volume V such that,

$$\mathrm{SSA} = S/m = \frac{S}{\rho_{ice} V}, \tag{1}$$

where ρ_{ice} is the density of pure ice (917 $\mathrm{kg/m^3}$ at 0° C) (Hagenmuller et al., 2016; Gallet et al., 2014). Snow SSA strongly affects absorption of infrared radiation. This relationship is evident from measurements of infrared reflectance that are highly correlated with snow SSA for various snow types (Domine et al., 2006). Among others, Gallet et al. (2009) and Gallet et al. (2014) exploit this correlation in the accurate determination of dry snow SSA and wet snow SSA, respectively, using 1.31 µm directional hemispherical reflectance measurements (1.55 µm for measurements of snow SSA > 60 $\mathrm{m^2kg^{-1}}$). Other studies establish techniques to accurately obtain snow SSA using methane gas absorption (Legagneux et al., 2002) and X-ray ~~computed microtomography (X-CT) to monitor the evolution of snow SSA in a high-temperature gradient (Wang and Baker, 2014) and~~ micro-computed tomography (X-CT) in ~~isothermal snow metamorphosis (Ebner et al., 2015)~~cold rooms (Pinzer and Schneebeli, 2009) . Matzl and Schneebeli (2006) also derive snow SSA using infrared photography. Other techniques that are nondestructive enable the rapid retrieval of snow optically equivalent grain size from field measurements. Gergely et al. (2014), for example, demonstrate an accurate technique to quickly determine the snow optically equivalent diameter from 0.95 µm bi-hemispherical reflectance measurements. Painter et al. (2007) infer snow optical grain radius (r_{eff}) from spectral hemispherical directional reflectance factor measurements using a contact probe and a spectrometer.

In snowpacks with high temperature gradients the diffusion of vapor causes snow SSA to decrease during the natural process of snow metamorphism (Flanner and Zender, 2006; Wang and Baker, 2014). In isothermal snow, highly faceted snow grains with relatively high SSA and low radii of curvature undergo coarsening in a process driven by the Kelvin effect. Ebner et al.

(2015) show that measurements of snow SSA evolution in isothermal snow agree with the isothermal snow ~~metamorphosis~~ metamorphism modeling framework developed by Legagneux et al. (2004) and Legagneux and Domine (2005). These studies express snow SSA in isothermal ~~metamorphosis as~~ metamorphism as a function of time t as follows,

$$\mathrm{SSA} = \mathrm{SSA}_0 \left(\frac{\tau}{\tau + t} \right)^{1/n}, \tag{2}$$

for initial snow SSA_0 at $t = 0$ and adjustable parameters τ and n. Domine et al. (2009), however, observe increasing snow SSA due to the fragmentation of surface snow grains mobilized by wind.

~~Previous studies establish techniques to accurately obtain snow SSA using methane gas absorption (Legagneux et al., 2002), contact spectroscopy (Painter et al., 2007), infrared hemispherical reflectance (Gallet et al., 2009; Picard et al., 2009; Gallet et al., 2014; Ge , and X-CT in cold rooms (Pinzer and Schneebeli, 2009; Wang and Baker, 2014; Ebner et al., 2015), but these methods require expensive, heavy equipment and measurements can be time consuming. Further, previous methods require that snow samples are collected and possibly even destroyed during measurements, preventing in situ snow observations over the span of just several hours. Because of the strong dependence of snow albedo on snow SSA (Adolph et al., 2017), the ability to obtain rapid, repeatable measurements that can describe the snow surface in basic physical terms is widely sought after~~Currently, it is still unclear how solar heating of snow by LAI affects possible negative feedbacks relating to temperature gradient metamorphism. The combined net effect of positive and negative feedback mechanisms within snowpacks is unknown and difficult to study in nature because measurement techniques easily disturb the natural snow structure. The question remains whether or not enhanced solar heating from LAI at the surface could slow metamorphism by weakening the temperature gradient and associated vertical flux of vapor. In light of these current unknowns, the purpose of this study is twofold: One, to investigate the effects of added LAI on snow albedo feedback; and two, to demonstrate the utility of a new instrument we use to obtain approximate snow SSA. We hypothesize that if we add dust and BC to snow surfaces, then we will induce measurable snow albedo positive feedback.

~~Here, we introduce a new technique to measure snow SSA in a nondestructive manner using 1.30 and 1.55 µm bidirectional reflectance. By gently placing~~ To test this hypothesis, we first describe the design principle and calibration of the Near-Infrared Emitting and ~~Reflectance-monitoring~~ Reflectance Monitoring Dome (NERD), an instrument that is placed gently onto the snow surface ~~,~~ to obtain snow SSA. The NERD enables multiple 1.30 and 1.55 µm bidirectional reflectance ~~factors (BRFs) are obtained~~ measurements in just minutes with minimal alteration of the snow ~~surface~~structure. To calibrate with respect to snow SSA, we compare snow BRFs with X-CT derived SSA ~~to identify the~~ and find an exponential relationship between SSA and snow 1.30 µm BRFs. These relationships are also explored using a three dimensional Monte Carlo photon transport model. We then present results from our LAI in snow experiments. We discuss these results and their implications. Overall, this study demonstrates conditions for which snow metamorphism can be enhanced by the presence of LAI.

2 Instrumentation and Methods

2.1 The Near-Infrared Emitting and Reflectance-Monitoring Dome (NERD)

The NERD is designed to measure 1.30 and 1.55 µm BRFs. ~~Four~~ These wavelengths are selected for snow SSA retrieval due to the strong dependence of snow albedo on snow optical grain size (i.e. sphere equivalent radius). Snow spectral albedo is simulated here using the SNICAR model to demonstrate this sensitivity (Fig. 1). While snow spectral albedo is sensitive to snow optical grain size (and thus snow SSA), it is not sensitive to small black carbon concentrations at these wavelengths. Snow SSA can therefore be retrieved using 1.30 µm and 1.55 µm reflectance measurements for snow with small black carbon concentrations.

The design principle is similar to the DUal Frequency Integrating Sphere for Snow SSA measurements (DUFISSS) (Gallet et al., 2009). The NERD also uses 1.30 (1.31 in DUFISSS) and 1.55 µm emitters to illuminate the snow surface from nadir (15 degrees off nadir for 1.55 µm in NERD). The main distinction between the DUFISSS and the NERD is the type of reflectance measured. Gallet et al. (2009) use an integrating sphere to measure hemispherical reflectance. In the NERD, however, photodiodes are directed toward the illuminated surface in a black dome to measure BRFs. The interior of the dome is painted with a flat black paint to increase absorptivity and minimize internal reflections between the dome and snow surface. Four infrared light emitting diodes (LEDs) ~~and four photodiodes~~ are mounted into a 17 cm diameter black styrene half-sphere~~(see Fig. 2).~~. Two LEDs with peak emission wavelengths of 1.30 µm are mounted at nadir and ten degrees relative to zenith ~~while~~ and two LEDs with peak emission wavelengths of 1.55 µm are mounted at 15 degrees off nadir ~~.~~ (see Fig. 2). 1.30 µm LEDs have spectral line half widths of 85 nm and half intensity beam angles of ten degrees, while 1.55 µm LEDs have half-maximum bandwidths of 130 nm and 20 degree beam angles. These high powered, narrow beam infrared LEDs are selected to illuminate a small oval ~~of~~ (estimated major axes of 1.5 cm at 1.30 µm and 3.0 cm at 1.55 µm) of the experimental surface to maximize the reflected radiance signal. The reflected radiance signal is measured using four InGaAs photodiodes mounted in two different azimuthal planes (0 and 90 degrees relative to the illumination); two each at 30 and 60 degrees relative to zenith. Photodiodes highly sensitive to light ranging from 800 to 1750 nm and relatively large active areas (1 mm) are selected to maximize sensitivity.

~~The NERD is similar to that of the DUal Frequency Integrating Sphere for Snow SSA measurements (DUFISSS) (Gallet et al., 2009) in that it uses 1.30 (1.31 in DUFISSS) and 1.55 µm emitters to illuminate the snow surface from nadir (15 degrees off nadir for 1.55 µm in NERD). LEDs are toggled using a Ruggeduino-ET (Extended temperature, operational down to -40 degrees C.; www.rugged-circuits.com/microcontroller-boards/ruggeduino-et-extended-temperature-40c-85c) connected to a LED driver. The LED driver generates an 80 mA square wave through each LED individually with a pulse width of two seconds (20 % duty cycle). The main distinction between the DUFISSS and the NERD is the type of reflectance measured. Gallet et al. (2009) use an integrating sphere to measure hemispherical reflectance. Here, rather, we direct photodiodes toward the illuminated surface in a black dome to measure BRFs. The interior of the dome is painted with a flat black paint to increase absorptivity and minimize internal reflections between the dome and snow surface. To detect reflected radiance signals, photodiodes are reverse biased to induce currents linearly related to the amount of light incident on its active region. Because these light signals are reflected from the experimental surface, the currents induced by the photodiodes are very small (nano- to micro-Amps).~~

~~To measure the small currents, the photodiodes are connected to transimpedance amplifiers (as in Fig. 2). The transimpedance amplifier circuits convert and amplify the small photodiode currents into measurable voltage signals. Finally, an active low pass filter is installed between the amplifier and the analog-to-digital converter (ADC) to reduce noise. This filter is designed to have a time constant of less than 0.5 seconds to achieve balance between adequate noise reduction and speed. Waiting 0.75 seconds after toggling the LED allows for enough time for the photodiode current to stabilize. After these currents stabilize, 100 voltage samples (ranging from 0.1 to 1.0 Volts) are then rapidly collected using the Ruggeduino-ET's ADCs. The average voltage obtained during active illumination is differenced from the average dark current voltage to derive reflectance factors. Because the~~ Because the orientation of LEDs and photodiodes are fixed, reflectance factors of surfaces with negligible subsurface scattering can be obtained after calibration using two diffuse reflectance targets in a manner similar to that used by Gallet et al. (2009), Gergely et al. (2014), and Dumont et al. (2010). These Lambertian targets reflect incident light according to Lambert's cosine law and appear equally bright at all viewing angles. ~~The reflectance of the targets are measured with high precision across a broad spectrum. At 1.30 (1.55) µm, the white and gray targets have calibrated reflectances of 0.95073 (0.94426) and 0.42170 (0.41343), respectively, as reported by the manufacturer.~~ By comparing the measured voltage signal from the experimental (snow) surface to that measured from the reflectance targets, two BRFs at both 30 and 60 degree viewing angles are obtained for each light source. ~~This~~ While subsurface scattering of visible light in snow is pervasive, the light penetration in snow near 1.30 and 1.55 µm is at most a couple centimeters due to the strong absorption features in the near-infrared. Subsurface scattering is assumed to be minimal and fully contained within each photodiode's field of view. Therefore, this procedure enables simultaneous measurements of multiple snow BRFs at 1.30 and 1.55 µm.

To validate NERD reflectance ~~measurements, we assess its~~ measurement accuracy, precision, and ~~responsivity by measuring~~ responsiveness, measured BRFs of reflectance standards are recorded after calibration. ~~Using both reflectance standards, we record ten BRF~~ Ten BRFs (R) ~~measurements~~ for each LED / photodiode viewing zenith angle ($\theta_i;\theta_r$) combination ~~during outdoor temperatures between~~ are measured in temperatures ranging from -20 ° ~~and~~ to +2 °C. In general, NERD BRFs of the Lambertian reflectance standards are accurate to within +/- 2 %. We quantify instrument precision (2 %) by computing root mean squared (RMS) ~~errors~~ differences from repeated measurements (see Table 1). Linear regressions quantify the linear ~~responsivity~~ response (A) over the reflectance range of 0.41 to 0.95. ~~Responsivity error~~ Response uncertainty ranges from -2 % to +3 % and from +1 % to +3 % at 1.30 and 1.55 µm, respectively. These ~~results validate~~ test results indicate the NERD's ability to obtain ~~precise BRFs~~ BRFs on smooth reflectance standards with a measurement uncertainty of 1-2 %.

2.2 ~~X-ray Microcomputed Tomography~~Snow Specific Surface Area Measurements

~~Snow BRFs measured by the NERD are complemented by X-CT scans. X-CT scans of snow are conducted at the U.S.~~

2.2.1 Snow samples

Surface snow (just the top few centimeters) samples were collected in nature over the span of three years (winters 2015-2017) and transported in coolers to the nearby US Army's Cold Regions Research Engineering Laboratory (CRREL) in Hanover, New Hampshire. ~~The machine is housed in a cold lab kept below 0~~Depth hoar samples, however, were instead grown inside the CRREL at -20 °C ~~allowing for~~ using a forced temperature gradient. Snow samples are classified based on X-CT ~~of snow without significant melt~~results according to Fierz et al. (2009) (Table 2).

~~Small samples of snow are collected in roughly 10 cm tall cylindrical plastic sample holders and placed into the machine. An~~

2.2.2 X-ray micro-computed tomography (X-CT)

To determine snow SSA, X-CT was conducted on a class of six snow samples according to Lieb-Lappen et al. (2017). X-ray ~~source is emitted at~~ (40-45 kV~~and~~ , 177-200 micro-Amps~~. X-ray transmittance is measured as the machine rotates the sample. Setting the exposure time~~) transmission through cylindrical snow samples was measured at rotation steps of 0.3-0.4 degrees. To limit scan times to 15 minutes, exposure time was set to 340 ms at a ~~pixel~~ cubic voxel resolution of 14.9 µm~~with rotation steps at 0.3-0.4 degrees allow for fast scan times of roughly 15 minutes. These short scan times are necessary to complete the scan without too much absorbed radiation melting the snow. Processing software allows for samples to be reconstructed while computing physical properties of which SSA are derived (Pinzer and Schneebeli, 2009). Three dimensional visualization software is used to generate images shown in Fig. 3.~~ . Processing software enables SSA calculations from three dimensional morphology results (Pinzer and Schneebeli, 2009).

2.3 ~~Snow Samples~~

~~Snow samples for NERD snow SSA calibration were collected over the span of three years (winters 2015-2017). Measurements of these samples were conducted during the months of February and March in 2016 and 2017 in Hanover, New Hampshire.~~

2.2.1 ~~Fresh samples from 2016~~

~~Fresh~~ In some cases, snow samples were ~~collected during a late winter snow fall event in 2016 just outside of Hanover, New Hampshire. Fresh snow from two different locations were scooped into coolers and then transported to the CRREL for analysis. Visual inspection of these samples revealed snow that appeared softer and less dense than the class of old samples . Because the surface temperature was close to 0° C., the samples appeared to be wet.~~ scanned several hours or days after snow BRFs were measured. To correct for natural isothermal snow SSA metamorphism while samples were being stored, eq. 2 was applied with t set equal to the total time elapsed between NERD measurements and X-CT ~~scans (Fig. 3a.) confirmed snow that was of relatively medium density (350 kg m^{-3}), medium porosity (62 %), and medium SSA (19 m^{2}kg^{-1}).~~ scan times and with τ and n inferred from Ebner et al. (2015).

2.2.1 ~~Artificial ice crystals grown in a cold lab~~Contact spectroscopy

~~One of the snow samples included in the NERD snow SSA calibration was grown inside a cold lab at -20° C. using a forced temperature gradient. Analysis on this sample was conducted during winter of 2016. Visual inspection revealed a hardened ice medium with~~ Snow SSA was also inferred from optical grain size measurements using contact spectroscopy

(Painter et al., 2007). Snow reflectance spectra are collected using an ASD FieldSpec4 and high-intensity contact probe with reference to a Spectralon white reference panel. The effective radius is determined from the normalized area of the absorption feature centered at approximately 1 nm using a look up table (Nolin and Dozier, 2000). These measurements were conducted on depth hoar created in a ~~well defined crystalline structure. X-CT scans (Fig. 3b.) showed jagged ice micro-features of relatively medium density (320 kg m^{-3}), medium porosity (65 %), and low SSA (9 m^{2}kg^{-1}).~~

2.2.2 ~~Old sintered samples from 2015~~

~~The oldest class of snow samples used for the NERD calibration were collected during the 2015 winter season in Hanover, New Hampshire. These samples were then stored in a cold laboratory for a year at the CRREL at approximately -20° C. During February of 2016, visual inspection revealed snow that was highly sintered. As expected, X-CT scans (Fig. 3c.) confirmed that these two samples, distinguishable only by the container they were stored in, were of relatively high density (610 kg m^{-3}), low porosity (33 %), and low SSA (9 m^{2}kg^{-1}).~~

2.2.2 ~~Fresh needles collected during the March 14 snow storm~~

~~On March 14, 2017, a heavy daytime snow fall event in Hanover, New Hampshire enabled rapid collection and analysis of snow samples. Cylindrical X-CT sample containers were placed in snow already on the ground. Snow fall filled sample containers in just a couple hours. Sample containers were carefully moved (with gloves) into coolers. Coolers were then rushed directly into the nearby lab for X-CT analysis. X-CT scans (Fig. 3d.) confirmed needle like ice structures. These structures presented a snow pack of relatively low density (110 kg m^{-3}), high porosity (88 %), and high SSA (66 m^{2}kg^{-1}).~~

2.2.2 ~~Fresh samples collected shortly after February (10-16) 2017 snow fall events~~

~~Moderately fresh snow samples were collected in the first couple days following snow storms in February 2017 in Hanover, New Hampshire. A few of these samples include snow with small amounts of added dust and BC. All samples with added LAI included in the NERD SSA calibration dataset were first screened to remove samples with heavy LAI loads that caused direct snow darkening at 1.30~~ cold lab (DH_2016) and ~~1.55 µm. Snow samples were shoveled into coolers and transported to the CRREL for X-CT analysis. X-CT scans (Fig. 3e.) revealed snow of relatively low density (170 kg m^{-3}), high porosity (82 %) and medium-high SSA (54 m^{2}kg^{-1}).~~

2.2.2 ~~Samples collected after apparent metamorphosis on February 17 2017~~

~~After visibly apparent snow metamorphosis, partially aged snow from Hanover, New Hampshire was collected and transported to the CRREL for X-CT analysis. Some of these samples include snow with added LAI. Samples with added LAI had shown visible signs of dramatic metamorphosis. X-CT scans (Fig. 3f.) confirmed these observations, revealing snow of relatively medium density (310 kg m^{-3}), medium porosity (66 %), and medium SSA (23 m^{2}kg^{-1}).~~ on rounded grains (RG_2015).

2.3 Monte Carlo Modeling of Bidirectional Reflectance Factors

The Monte Carlo method ~~for photon transport is used to model~~ is applied in this study to numerically simulate light emission by the NERD and the resulting three dimensional light scattering within ~~a snow pack. NERD LEDs are modeled as photon emitters according to their placement within the dome. An array~~ modeled snow packs. Arrays of photons with wavelengths generated at random using ~~a Gaussian distribution~~ Gaussian distributions are used to mimic the 85 and 130 nm full width at half-maximum spectral emission characteristics of the narrow-band LEDs ~~.~~ mounted in the NERD. These LEDs are modeled as photon emitters according to their orientation in the dome. Photons are initiated downward into the snow medium ~~(Kaempfer et al., 2007)~~ , as demonstrated by Kaempfer et al. (2007), and propagated in optical depth space. Photon particle interactions are determined using random number generators ~~and photons~~ . Photons can either be absorbed or scattered with the probability determined by the particle single ~~scatter~~ scattering albedo. Photons are terminated upon absorption and followed if scattered. When a photon is scattered, its new direction cosines are determined by the ~~specific~~ particle scattering phase function.

~~To generate theoretical calibration curves mapping snow BRFs to snow SSA,we run multiple simulations for various particle SSA ranging from 10 to 90 m^{2}kg^{-1}. At least 100 thousand~~ 1,000,000 photons per simulation are propagated and followed through the snow medium until they are absorbed or exit the medium. The snow ~~medium is modeled as a homogenous matrix~~ packs are modeled as homogenous matrices of suspended particles with input data containing the particle mass absorption cross section, asymmetry parameter, single scattering albedo, projected area, volume, and scattering matrix ~~from Yang et al. (2013). Ice~~ . These scattering properties are calculated by Yang et al. (2013) for randomly oriented ice particle shape habits ~~include spheres,~~ that include droxtals, solid hexagonal columns, and ~~solid hexagonal plates.~~ spheres. For spheres, we apply the Henyey-Greenstein phase function

$$P_{\mathrm{HG}}(\cos\theta; g) = \frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}}, \tag{3}$$

where θ is the scattering angle and g is the relevant asymmetry parameter. We select these subset of shape habits from the larger dataset provided by Yang et al. (2013) because they are purely convex solid ice particles. Because they are convex bodies, their SSAs can be computed from the projected area and volume. ~~To generate theoretical calibration curves mapping snow BRFs to snow SSA, we run multiple simulations for various particle SSA ranging from 10 to 90 m^{2}kg^{-1}.~~

~~Reflected light from Lambertian surfaces is simulated using the Monte Carlo model to test its statistical uncertainty. To this end, azimuthal~~ Azimuthal mean BRFs are calculated according to the reflectance definitions presented by Dumont et al. (2010) Hudson et al. (2006), and ~~?~~ Nicodemus et al. (1977). Accordingly, photon exit angles are grouped into 30 exit zenith angle (θ_r) bins at three degree resolution. Azimuthal mean BRFs are calculated by zenith angle θ_r from the total incident photon flux Φ_i by

$$R(\theta_i;\theta_r) = \int_0^{2\pi} \frac{d\Phi_r}{2\sin\theta_r \cos\theta_r \Phi_i} d\phi_r \tag{4}$$

where Φ_r represents the azimuthally integrated photon flux through each θ_r bin. In the denominator, the $\cos\theta_r$ factor satisfies Lambert's cosine law while $\sin\theta_r$ accounts for the zenith angular dependence of the azimuthally integrated projected solid angle. Finally, the factor two is necessary to normalize the resulting weighting function $w(\theta_r) = \sin\theta_r \cos\theta_r$, as

$$\int_0^{\pi/2} \sin\theta_r \cos\theta_r d\theta_r = \frac{1}{2}. \tag{5}$$

Monte Carlo noise is tested by computing BRFs from simulations of Lambertian surfaces. Azimuthal averaging reduces the BRFs' dimensionality, so that fewer photons are needed to mitigate Monte Carlo noise. Equation (5) is applied to Monte Carlo simulations of 75 thousand photons reflected by Lambertian surfaces having reflectances of zero to one. At three degree resolution, 30 and 60 degree BRFs of Lambertian surfaces are simulated accurately to within +/- 2 %. Monte Carlo noise from 75 thousand photons are quantified by computing RMS ~~errors~~ differences across the full range of Lambertian reflectances. Across this range, RMS ~~errors~~ differences at 30 and 60 degrees are generally less than 0.01. These ~~relatively small RMS errors computed from just~~ results indicate that at least 75 thousand ~~simulated photons justify computing accurate BRFs~~ photons are needed to mitigate Monte Carlo noise and sufficiently simulate accurate BRFs for Lambertian surfaces at three degree resolution. In a few additional test cases, simulating snow BRFs with up to 10,000,000 photons did not significantly change results when compared with simulations of 250,000 photons.

3 ~~Results and Discussion~~

~~To examine the relationship between snow SSA and 1.30~~

2.1 LAI in Snow Experimental Procedure

Snow BRFs and ~~1.55 µm BRFs, we compare~~ SSA were measured throughout the day in the following dust and BC in snow experiments. Sand particles and hydrophobic BC were sifted multiple times to filter out larger particles. The filtered LAI were then deposited onto experimental snow plots in an open field in Hanover, New Hampshire on February 10 and February 16, 2017 shortly after fresh snowfall events. For each experiment, one square meter plots of snow were designated as natural (control) or contaminated (experimental). BRFs and SSA are obtained using the NERD and from X-CT ~~derived snow SSA with NERD snow measurements. To this end,we conduct side-by-side X-CT and NERD analysis of all snow samples described in the preceding section. In general,NERD BRFs are directly related to snow SSA (Fig. 4). At 1.30 µm, NERD snow BRFs are slightly higher at 60 degrees than at~~ analysis, respectively. For each set of NERD measurements, 30 ~~degrees. Despite the direct relationships between NERD snow BRFs and X-CT derived snow SSA , there exists considerable spread in measurements at both wavelengths and at both viewing angles. The spread in measurements results in considerable uncertainty in the ability to retrieve snow SSA from NERD BRFs. In the following subsections, we discuss NERD reflectance measurement validation and results from Monte Carlo simulations in the context of previous studies. Finally, we synthesize our findings in a subsection that gives an analytical calibration function relating NERD BRFs to snow SSA and discuss measurement uncertainty.~~ degree and 60 degree BRFs are both recorded four times. BRFs are measured over two different locations within the experimental plot using two photodiodes at each viewing angle (30 and 60 degrees).

2.2 ~~Reflectance Measurement Validation~~

~~Using the NERD, we can obtain relatively accurate snow BRF measurements in nature without drastically affecting the snow. By recording measurements across two view azimuth angles and additional scattering planes by rotating the dome, we can assess azimuthal anisotropy in just a few minutes.~~

2.1.1 February 10 experiment (cloudy sky / diffuse ambient lighting)

Early on February 10, experimental plots were loaded with BC until visible darkening was apparent. Snow BRFs were measured shortly after 00:00, 03:00, 06:00, and then periodically throughout the day. Because these plots were well shaded by tall trees, these measurements were used to monitor snow metamorphism without the influence of direct solar illumination. Furthermore, ~~by measuring multiple BRFs across multiple locations of a snow surface, we obtain numerous samples spanning multiple azimuthal planes that also enables easy characterization of the spatial variability in snow BRFs. Repeating rapid measurements in this manner allow us to obtain relatively accurate snow BRFs . Multiple precise measurements allow quantifying relatively large BRF variations associated with azimuthal anisotropy and spatial heterogeneity. Median BRFs reported across a unique wavelength, LED position, and photodiode zenith angle give a second order approximation of the snow azimuthal mean BRF. Computing RMS errors from these uniquely defined wavelength-BRF combinations quantifies measurement uncertainty. To this end, we first test NERD accuracy, precision, and responsivity by testing with idealized Lambertian surfaces before obtaining snow BRFs~~ mostly cloudy conditions on February 10 diffused incoming radiation so that ambient lighting was nearly isotropic. ~~Results in Table 1 indicate that any single NERD reading is subject to measurement uncertainty of about +/-2 %. Although measurement uncertainty prevents us from using the NERD to obtain highly accurate BRFs , NERD BRF measurements are accurate and precise enough to observe relatively large variations in snow BRFs that are of particular interest in this study.~~

~~Compared to the Infrasnow (Gergely et al., 2014), NERD BRF measurements of Lambertian surfaces are slightly less accurate. In a similar validation experiment, Gergely et al. (2014) measure the reflectance of 0.25, 0.50, and 0.99 reflectance standards accurately to within less than 1 %. Gergely et al. (2014) use an integrating sphere that enables directional-hemispherical reflectance factor measurements at 950 nm in contrast to~~

2.1.2 February 17 experiment (clear sky / direct solar heating)

On February 17, just a pinch of BC and 30g of sand were deposited on separate experimental plots. These surface fluxes were selected to mimic extreme LAI deposition events observed by Skiles and Painter (2017). As in the ~~1.30 and 1.55 µm BRFs measured by the NERD. Both instruments make use of Lambertian reflectance standards for calibration and testing. Although each instrument uses a different wavelength and measures a different type of reflectance factor, testing on Lambertian reflectance standards with constant bidirectional reflectance distribution functions (BRDFs) allows for easy comparison of measurement uncertainty across multiple measurement techniques.~~ previous experiment, snow BRFs were measured periodically throughout the day, however, all snow plots were in full view of the clear sky to maximize incident direct solar irradiance.

~~Dumont et al. (2010), for example, use Lambertian reflectors to report a BRF measurement accuracy of better than 1 % using a high angular resolution spectrogonioradiometer. Gallet et al. (2009) also use similar Lambertian standards to calibrate 1.31 and 1.55 µm directional-hemispherical reflectance factor measurements. Gallet et al. (2009) use six standards to parametrically fit signal voltages to reflectance values. This approach accounts for nonlinear responsivity due to re-illumination of the standards through multiple scattering within the integrating sphere. While NERD responsivity is not perfectly linear, we expect re-illumination of the surface through multiple scattering within the black dome to be minimal.~~

~~Although photodiode responsivity varies with temperature, frequent calibration minimizes these errors. Therefore, the main source of NERD responsivity error is likely due to small deviations in light output from the LEDs. Like almost all electronic circuit elements, LED performance is also a function of its temperature. In its operational mode, the NERD drives the user selected active LED with a current pulse width of two seconds. When the duty cycle is increased to 50 % (two seconds on, two seconds off), we observe drift in the photodiode response. This responsivity drift is mitigated, but not completely eliminated, when the duty cycle is decreased to 20 % (two seconds on, eight seconds off) . Because we observe these responsivity errors in testing shortly after calibration, we speculate that changing LED temperatures can affect the the light output enough to cause a one to two percent measurement error.~~

2.2 ~~Monte Carlo Results~~

~~At~~

3 Results and Discussion

3.1 Monte Carlo modeling

To validate the Monte Carlo model for snow applications, 1.30 µ~~m, 30 degree snow BRFs measured with the NERD for various snow SSA fall within the envelope of shape habits derived from Monte Carlo simulations. Monte Carlo simulations of spheres, droxtals , and hexagonal columns accurately predict 30 degree BRFs measured by the NERD for snow SSA ranging from 10~~ m narrow band black-sky albedo was calculated and compared to the SNICAR model for snow Re ranging from 36 to 327 µm (SSA = 80 to ~~70~~ 10 m^{2}kg^{-1}) (see Fig. 3, left). As expected, Monte Carlo results from snow modeled as spherical ice particles were consistent with narrow-band albedo calculations from Flanner et al. (2007). These results show slightly higher hemispheric reflectances for droxtals (for all SSA) and solid hexagonal columns (for SSA $>$ 40 m^{2}kg^{-1}~~. Monte Carlo simulations predict lower BRF values at 60 degrees than at 30 degrees. These results provide an estimate of the uncertainty associated with deriving snow SSA from NERD BRFsacross various shape habits and snow samples~~) than those calculated from equal SSA spheres and from the SNICAR model. We hypothesize that the variations in these albedo calculations, and also BRFs, across particle shapes are inversely related to the particles' asymmetry parameters.

~~At 1.55 µm snow SSA values~~ To inform on our choice of a snow SSA calibration function, Monte Carlo simulated snow BRFs are calculated for various (homogeneous) particle SSA ranging from 10 to ~~70~~ 80 m^{2}kg^{-1} ~~yield lower Monte Carlo~~

~~simulated BRFs than what is measured by the NERD. Comparing 30 and 60 degree viewing zenith angles, Monte Carlo results are more similar at~~ and plotted against measurement data in Fig. 4. Generally, we found exponential (linear) relationships between 1.30 (1.55) µm ~~than at~~ BRFs and snow SSA for spheres, droxtals, and solid hexagonal columns. 1.3 µm BRF calculations are slightly higher at 30 degrees than at 60 degrees for particle SSA > 30 m^2kg^{-1}. At 1.30 ~~µm. The relationships between 1.55~~ µm~~BRFs and snow SSA are also more linear than those at~~ , measured 30 degree snow BRFs for varying snow SSA fall within the envelope of modeled BRFs for all three shape habits. These modeling results are in closest agreement with measurements at 30 degrees viewing for 1.30 µm. ~~Stronger linearity at~~ At 1.55 µm, ~~however, does not necessarily imply more accurate~~ measured BRFs are larger than predicted from modeling across all SSA.

3.2 NERD Snow SSA Calibration

To calibrate the NERD for snow SSA retrieval~~. Obtaining snow SSA at~~ , we compare X-CT derived snow SSA with NERD snow BRF measurements (see Fig. 4). In general, snow BRFs are directly related to snow SSA. At 1.30 µm BRFs range from just under 0.2 (for low SSA) to as high as 0.7 (for high SSA) and are slightly higher at 60 degrees than at 30 degrees. We observe 1.55 µm ~~is more difficult due to the lesser span and lower responsivity of~~ snow BRFs close to 0 (for low SSA) and as high as 0.2 (for high SSA). We observe the highest 1.55 µm snow BRFs at ~~this wavelength~~60 degrees for fresh snow (needles).

3.3 ~~NERD Snow SSA Calibration~~

~~In general, snow SSA results from X-CT scans are related to NERD~~ These results show considerable spread across snow samples in BRF measurements and across shape habits in Monte Carlo calculations at both wavelengths and at both viewing angles. The spread in measurements, in particular, indicates a considerable uncertainty in the ability to retrieve snow SSA from NERD BRFs. While the 1.30 µm~~nadir illuminated BRFsvia an exponential relationship. This relationship exists at both the~~ , 30 ~~and~~ degree viewing zenith angle BRF combination most closely agrees with modeled BRFs, a similar margin of error at the 60 degree viewing zenith ~~angles. At 1.55 µm, snow SSAresults from X-CT scans are related to NERD 15 degree, off nadir illuminated BRFs via linear relationships. The relationship between snow SSA and NERD measurements is most clear and robust at 1.30 µm. Nadir illumination at 1.30 µm results in the best snow SSA agreement across NERD observations and Monte Carlo modeling at the~~ angle can provide a second estimate of snow SSA. Reporting two snow SSA values using both view angles can provide an estimate of the variability in SSA retrieval resulting from the angular dependence of the snow BRDF in the near-infrared. Monte Carlo 30 degree ~~viewing angle.~~ BRFs are larger than 60 degree (viewing; zenith) BRFs. These results are consistent with those from Kaempfer et al. (2007), but at 900 nm.

Our finding of the exponential ~~relationship~~ relationships between snow SSA and 1.30 µm BRFs is consistent with results from previous studies (Picard et al., 2009; Gallet et al., 2009). ~~Likewise, Gallet et al. (2009)~~ Gallet et al. (2009) also identify a linear relationship between 1.55 µm reflectance and snow SSA ~~. These studies, however, quantify snow SSA from hemispherical reflectances instead of BRFs. Hemispherical reflectance measurements theoretically reduce measurement variations associated with grain shapes. Picard et al. (2009) conclude that obtaining snow SSA from snow albedo measurements are subject to as much as 20 percent error when grain shape is unknown. This relatively large source of error due to grain shape~~

~~is further explored here in Monte Carlo derived albedo calculations for snow surface of spheres, droxtals, solid hexagonal columns, and hexagonal plates (Fig. 5).~~

~~As expected, snow modeled as spherical ice particles, simulated in the Monte Carlo model using the Henyey-Greenstein phase function~~

$$P_{\mathrm{HG}}(\cos\theta; g) = \frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}},$$

~~where θ is the scattering angle and g is the relevant asymmetry parameter, most closely agrees with 1.30 and 1.55 µm narrow band black-sky snow albedo calculated from the Snow, Ice, and Aerosol Radiation (SNICAR) model (Flanner et al., 2007). Snow albedo dependence on grain shape is consistent at both wavelengths. In general, droxtals yield higher reflectances. Reflectances of solid hexagonal columns agree closely with spheres and SNICAR at both wavelengths for snow SSA lower than 40~~ and use the longer wavelength in their DUFISSS to obtain measurements of high snow SSA (> 60 m^{2}kg~~$^{-1}$, after which they tend toward reflectances similar to droxtals. Finally, hexagonal plates yield low reflectances. Low reflectances at both wavelengths are due to the extremely sharp forward scattering peak of these plates. Although highly idealized and perfectly smooth, these shape habits demonstrate the relatively large hemispherical reflectance variations across snow grain shape. These large variations in reflectance across grain shape are the largest source of uncertainty in snow SSA measurements using infrared reflectance. Monte Carlo modeling of~~ $^{-1}$). In this study, however, nearly all snow samples are lower than this threshold. A possible follow on study would include snow of higher SSA to determine the utility of 1.55 µm snow BRFs in ~~Fig. 4 also suggest these uncertainties exist for directional reflectance measurements. These uncertainties associated with unknown grain shape limit accuracy of NERD SSA retrieval.~~ measuring fresh snow of extremely high SSA particularly common in the extremely cold Arctic and Antarctic environments and observed by Legagneux et al. (2002) and Libois et al. (2015).

~~Surprisingly,~~ Snow BRFs at 1.55 µm ~~BRFs measured~~ observed by the NERD are higher than ~~predicted by~~ both hemispherical reflectance measurements by Gallet et al. (2009) and those predicted from Monte Carlo modeling. ~~Using the NERD , we observe 1.55 µm snow BRFs as high as 0.2. We measure the highest 1.55 µm snow BRFs at 60 degrees for particularly fresh snow, but high 1.55 µm BRFs are larger than simulated for all SSA. Because of its relatively high instrument precision (Table 1), these seemingly high BRFs are probably accurate. The primary contributor for the discrepancies against models at this wavelength is possibly due to the broad spectral emission characteristics of the 1.55 µm LEDs . With~~ NERD LEDs have full width at half maximums of 130 nm ~~,~~ and emit non-negligible light ~~emission~~ at wavelengths much shorter, toward the near-infrared~~, is a likely cause of~~ . We hypothesize that higher than expected ~~reflectances. Although the spectral emission characteristics of NERD LEDs are simulated in Monte Carlo simulations using Gaussian photon wavelength distributions, and in SNICAR using a simple normalized Gaussian weighting function, non-negligible light emission from the tails of these distributions is possibly under estimated. Because of the expected sharp increase in snow reflectance as wavelength decreases from~~ measured 1.55 ~~to 1.30~~ µm ~~(Wiscombe and Warren, 1980; Flanner et al., 2007), it is possible that even a small amount of light emission at wavelengths toward the near-infrared can have a measurable effect on snow BRF observations. This effect is further explored in~~ BRFs are caused by reflected light at shorter wavelengths. Additional SNICAR modeling results and Monte Carlo simulations ~~by broadening the Gaussian distribution of photon wavelengths and in SNICAR by broadening the~~

~~Gaussian weighting function applied to narrow-band albedo calculations. These calculations confirm this hypothesis , as 1.55 µm narrow band albedo with a full width at half maximums of 0.26 µm (doubled from 0.13 µm) closely agree with NERD BRF measurements. This finding suggests light emission from the 1.55 µm LEDs is non-negligible at shorter, more absorptive wavelengths~~support this hypothesis (see Fig. 3, right).

~~Notwithstanding the limitations associated with retrieving precise snow SSA from BRFs, we generate an analytical calibration function relating snow SSA to NERD BRFs. To this end, we propose the~~ In light of these empirical and numerical results, we propose the following general exponential form ~~for~~ relating 1.30 µm snow BRFs to SSA, such that

$$\mathrm{SSA} = \alpha \exp(R_{1.30}) + \beta \tag{6}$$

for ~~predicted snow SSA and~~ 1.30 µm snow BRF $R_{1.30}$. Using least squares regression analysis, we compute parameters α and β for both 30 and 60 degree viewing zenith angles ~~. At 30 degrees, setting α = 88.7 and β = -103 minimizes residuals and results in a snow SSA RMS error of 7.05 m^{2}kg^{-1} (Fig~~(see Fig. 5).

Ideally, an empirically derived calibration function would include SSA measurements from multiple methods to mitigate uncertainties associated with collection methods needed for X-CT analysis. Such collection methods can easily change the snow microphysical characteristics and lead to biases in the X-CT derived SSA. As a preliminary validation of eq. 6~~, left). At 60 degrees, setting α = 91.7 and β = -113 minimizes residuals and results in a snow SSARMS error of 7.23 m^{2}kg^{-1} (Fig. 6~~, ~~right).~~ we compare snow SSA results to SSA derived from snow optical effective radii measurements conducted using contact spectroscopy in Fig. 5. Encouragingly, two out of three measurements fall within the bounds of the standard error of the regression. As expected, contact spectroscopy snow SSA values are consistently higher than those calculated from X-CT analysis and therefore eq. 6. Because contact spectroscopy measurements typically yield higher SSA values than those derived from other optical methods, these comparisons, though preliminary, offer some initial validation of the NERD snow SSA calibration.

~~This margin of uncertainty regarding SSA retrieval from snow infrared reflectance measurements falls within the expected range reported in previous studies (Picard et al., 2009; Gallet et al., 2009). This analysis complements previous studies and indicates that retrieval of highly precise snow SSA using NERD measurements is unlikely. Obtaining approximate estimates of snow~~ Hereafter, we apply eq. 6 in the following LAI in snow experiments to estimate hourly snow SSA from measured snow BRFs. Because the remainder of this study is concerned with relatively large changes in SSA, approximate SSA ~~using NERD measurements across a wide variety of snow types, however, is highly likely. Because of its non-destructive nature, rapid, repeatable retrieval of approximate snow SSA~~ retrieval using the NERD ~~will be useful for studying hourly-scale snow metamorphosis (Fig. 7) . While the~~ are sufficient to quantitatively assess snow metamorphism in the presence of LAI.

3.3 LAI enhanced snow metamorphism

First, to monitor snow metamorphism without solar heating, during the early morning (night) hours on February 10, we deposit BC onto an experimental plot after the previous day's snow fall. Surface temperatures ranged from -14 to -9 °C. We observed low to moderate wind speeds from the early morning hours through the afternoon with partly to mostly cloudy conditions during the day. BRFs measured at 1.30 (1.55) μm ~~, 30 degree viewing zenith angle BRF combination most closely agrees with modeled BRFs, a similar margin of error at the 60 degree viewing zenith angle can provide a second estimate of snow SSA. Reporting two snowSSA values using both view angles can ultimately give observationalists an idea of the variability in SSA retrieval resulting from the angular dependence of the snow BRDF in the near-infrared.~~ remained within 0.5 and 0.6 (0.1 and 0.2) throughout the day in both contaminated and natural snow (see Fig. 6). X-CT analysis showed small differences in morning (49 $\mathrm{m^2kg^{-1}}$) and afternoon (48 $\mathrm{m^2kg^{-1}}$) snow SSA. Our results from this experiment indicate that heavy BC loading had little to no effect on snow metamorphism without direct solar irradiance.

~~While these results minimize the usefulness of obtaining snow SSA from~~ Second, to monitor snow metamorphism occurring after forced large BC and dust deposition events under direct solar illumination, on February 17, we set up a similar experiment in full view of the sun. Surface temperatures ranged from -4 to +2 °C. We observed minimal wind speeds and cloud cover resulting in calm, clear sky conditions. In natural snow, BRFs remained close to 0.5 throughout the day, with the lowest values (0.49) recorded in the afternoon (13:00 EST) and the highest values (0.55) recorded in the morning (08:00 EST) and evening (17:00 EST). 1.55 μm ~~snow BRFs , it is worth noting that Gallet et al. (2009) use~~ BRFs remained just above 0.1. In the dust loaded plot, snow 1.30 (1.55) μm ~~in their DUFISSS to obtain measurements of large SSA snow ($>$ 60~~ BRFs decreased rapidly from above 0.5 (0.1) before 10:00am to to below 0.3 (0.05) by 1:00pm EST. We found less extreme metamorphism in the lightly contaminated snow with added BC, as BRF measurements decreased from above 0.5 (0.1) to below 0.45 (0.1). 1.30 μm BRFs slightly increased thereafter (from 13:00 to 17:00 EST) in both natural and contaminated snow (see Fig. 7). Snow SSA also decreased throughout the day. From X-CT analysis, we found morning snow SSA to be about 50 $\mathrm{m^2kg^{-1}}$~~). Here, nearly all snowsamples used in the NERD SSA calibration were lower than this threshold. A possible follow on study would include snow~~ , which thereafter decreased to 41, 23, and 18 $\mathrm{m^2kg^{-1}}$ in natural, BC loaded, and dust loaded snow, respectively. NERD derived SSA appears to be biased low in the afternoon dust loaded plot. This bias might be an indication of the presence of liquid water that was also visible to the naked eye. X-CT scans performed on this snow sample are representative of refrozen snow and do not conform to the isothermal snow SSA correction (eq. 2) applied to snow samples scanned several hours after collection. In BC loaded plots, we observed a large spatial heterogeneity in measurements, indicating that small BC deposition has a powerful localized effect on snow metamorphism.

These results suggest that realistic LAI deposition can accelerate snow metamorphism. The primary cause of this accelerated process is enhanced solar radiation by LAI. Surprisingly, added BC had little to no effect on snow metamorphism during cloudy conditions. One possible explanation of this surprising result is that adding BC to snow only initiated melting during clear sky conditions. In the clear sky experiments, LAI enhanced solar absorption at the surface which warmed the snowpack. As the snow surface began to melt, near-infrared reflectance decreased rapidly. Rapidly decreasing near-infrared reflectance is indicative of either the accumulation of liquid water from melting snow or decreasing snow surface SSA.

Accelerated snow metamorphism by dust loading is consistent with the findings of Skiles and Painter (2017). The indirect effect of LAI on snow is also demonstrated by Hadley and Kirchstetter (2012), where the albedo reduction due to the presence of BC in snow is amplified in snow of ~~higher SSAto determine the utility of 1.55 μm snow BRFs in measuring fresh snow of extremely high SSAparticularly common in the extremely cold Arctic and Antarctic environments as in Legagneux et al. (2002)~~

~~and Libois et al. (2015).~~ lower SSA. This enhancement of snow albedo reduction is another source of instability in the snow pack that increases the strength of snow internal albedo feedback. Typical BC deposition events are very small, however, so it is difficult to reproduce natural BC concentrations when adding any BC to a one square meter plot.

4 Conclusions

Taken together, these results indicate that LAI deposition can accelerate snow metamorphism and enhance positive snow albedo feedback, especially during cloud free, calm weather conditions when surface air temperatures are near 0°C. To obtain quick, ~~accurate, reliable, and~~ repeatable measurements of snow SSA without destroying samples, we engineered an instrument ~~that measures snow~~ (i.e., the NERD) that measures 1.30 and 1.55 µm BRFs ~~. By flashing narrow band LEDs centered around these wavelengths, light reflected by experimental snow surfaces is measured using photodiodes mounted at 30 and 60 degrees relative to nadir. Photodiode currents are converted into measurable voltage signals enabling calibrated BRF calculations using Lambertian reflectance targets. Monte Carlo modeling and X-CT derived snow SSA help to demonstrate the relationship between snow BRFs and SSA . Generally, we found an exponential relationship between~~ of snow. We evaluated NERD accuracy, precision, and responsiveness by testing with idealized Lambertian surfaces before obtaining snow BRFs. Notwithstanding the limitations associated with retrieving precise snow SSA from BRFs, we proposed an analytical calibration function relating snow SSA to 1.30 µm BRFs~~and snow SSA. These results demonstrate the NERD's ability to obtain~~ . Our results lead to the conclusion that the NERD can provide estimates of snow SSA to within +/- ~~7~~ 10 m^2kg^{-1}~~without destroying snow samples. This nondestructive technique for snow SSA retrieval will be useful in science applications that involve hourly scale monitoring of snow SSA. Applying the NERD will be especially useful in experiments designed to learn about~~ .

The NERD will serve to further study the effects of LAI on snow ~~metamorphosis~~ metamorphism and to explore the spatial heterogeneity of snow SSA. Because it can also operate quickly, NERD measurements ~~will also~~ can complement satellite borne observations during narrow sampling windows. To fulfill these pursuits, however, a more comprehensive snow SSA measurement validation is needed. Additional independent measurement methods that include snow samples with a larger snow SSA span from a variety of environmental conditions and further experimentation into the small scale effects on NERD snow BRF measurements are needed to fully justify the NERD as an accurate snow SSA measurement technique. Further investigation into the micro-physical limitations and quantitative uncertainties associated with the precise retrieval of snow SSA from near-infrared BRF measurements is the subject of a follow-on study.

Code and data availability. Plot data referenced in this manuscript and associated Python scripts used to generate figures are made available via the University of Michigan's Deep Blue data repository (Schneider and Flanner, 2018).

Appendix A: NERD Photodiode Current Amplifiers

~~The objective of this appendix is to show that for convex bodies, sphere effective radii r_{eff}, as defined in Eq. (2), and RE, as defined in Eq. (3), are equivalent. In Vouk (1948), it is shown that for convex bodies,~~

$$S = 4\bar{A},$$

~~where $\bar{A}$ is the average projected area of the convex body. Substituting Eq. (A1)into Eq. (1) then gives~~

$$\mathrm{SSA} = \frac{4\bar{A}}{\rho_{ice} V}.$$

~~Equating Eq. (2) and Eq. (A2) and simplifying,~~

$$3/r_{eff} = \frac{4\bar{A}}{V}.$$

~~Finally, solving Eq. (A3) for r_{eff} gives~~

$$r_{eff} = \frac{3}{4}(V/\bar{A}),$$

~~which is equivalent to the expression for RE given in Eq. (3) , thus concluding the proof.~~ To detect reflected radiance signals, photodiodes are reverse biased to induce currents linearly related to the amount of light incident on its active region. Because these light signals are reflected from the experimental surface, the currents induced by the photodiodes are very small (nano- to micro-Amps). To measure the small currents, the photodiodes are connected to transimpedance amplifiers. The transimpedance amplifier circuits convert and amplify the small photodiode currents into measurable voltage signals.

Two NERDs are engineered with different photodiode current amplifications. Photodiode current amplification is determined by the feedback resistance in the transimpedance amplifier circuits. Active low pass filters are applied between the amplifier and the analog-to-digital converter (ADC) to reduce noise. This filter is designed to have a time constant of less than 0.5 seconds to achieve balance between adequate noise reduction and speed.

Competing interests. Mark Flanner is currently an editor for *The Cryosphere*. We are not aware of any other competing interests associated with the publication of this manuscript.

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