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Discussions

Interactive comment on "First Sentinel-1 detections of avalanche debris" by E. Malnes et al.

E. Malnes et al.

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Response to Anonymous referee #1. By: Eirik Malnes, Markus Eckerstorfer and Hannah Vickers

It might not be common practice to immediately respond to a referee comment. However the referee criticises the novelty in the research, questions the soundness of methods applied and effectively suggests rejecting the paper. We think, however, that this research is novel and merits publication, and is suitable for the broad readership of The Cryosphere. There is some constructive criticism that we would like to use for further improvement of the manuscript. However, we choose here to respond to all major comments, as we break them down into sections below:

1: "The study is limited temporally to one avalanche episode that took place in late December 2014/early January 2015, and spatially to a sub-region of northern Norway".

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This is technically correct. We report an analysis of a single, however, extreme snow avalanche cycle that occurred in Northern Norway. Avalanches are – as many other natural hazards – rare in occurrence. Documentation of avalanche cycles of such magnitude, as reported in our manuscript, are therefore of high scientific interest. Moreover there is an applied interest from road authorities and avalanche forecasting services. Due to the recent availability of Sentinel-1A (S1A) data, we were and are still confident that our manuscript would attract attention from a broad readership, which The Cryosphere certainly has. However, we will address the importance of our contribution in a better way in a revised manuscript. Lastly, we think that reviewer 1 desires a methodology paper, which certainly would belong in a remote sensing journal. Furthermore, spatially complete datasets on avalanche activity are still largely missing, and not achievable with conventional field methodologies. This limits meaningful statistical analysis and operational avalanche forecasting. Our aim was therefore to build the basis for further research and development in an innovative, fast growing field that potentially improves avalanche risk reduction. We therefore do not think that this study is "limited" by a sub-region of Northern Norway, which is in fact covering 250 x 150 km of largely inaccessible mountain terrain, spanning over two counties and 9 out of 11 avalanche forecasting regions in Troms County. Such a large spatial coverage is unprecedented in SAR avalanche detection. Our study is furthermore not "limited" by a single avalanche "period", as we report from the most significant avalanche cycle in Norway in the winter 2014/15. We note that reviewer 1 uses the term "period" whereas "avalanche cycle" is a more correct term in the avalanche science community.

2: "Validation is limited to photo-graphic documentation of a few avalanche sites, inadequate for a sample that includes several hundred avalanche sites, and insufiﬁcient for assessing the probability for correct/incorrect classiﬁcations and for quantifying the percentage of missing detections." Naturally, validation is limited to a few avalanche sites in a region that is comprised of mostly inaccessible avalanche terrain. Traditional field observations have the disadvantage of bias towards safe, accessible locations under good visibility. In our case, we first did the manual avalanche detection using

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S1A data, and then visited the easily accessible valleys Breivikeidet (Fig. 1a, Fig 2a, Fig. 4) and Lavangsdalen (Fig 3 and 5) to validate our detections. Note that all SAR detected avalanches could be validated in the field (100 % correct detection). Another source of validation could have been comparisons with high resolution optical data. These were, however, out of the question in this case due to polar darkness at our latitudes. We have previously used Landsat-8 for validation of larger avalanches in more favorable light conditions, but again imagery is not available due to polar darkness. For a limited campaign we even tried out aerial photo from an unmanned aerial vehicle (UAV), but also here the image quality and spatial extent were too poor to add new evidence to our study. The majority of the S1A swath was simply not accessible to us in a safe and non-time consuming manner. Moreover, field validation of all SAR detected avalanches would obviously completely miss the point of a remote sensing study. Here, we are trying to show that by using space-borne SAR, a spatial overview of avalanche activity from an avalanche cycle is possible. We furthermore collected GPS tracks of the avalanche outlines from two accessible avalanches, which perfectly matched the backscatter outlines in the S1A data. This gives a good estimate on how accurate manual avalanche detection is. The third means of validation is the manual detection of avalanche debris in RS-2 Ultrafine data confirming the S1A detections. All S1A detections could be validated with the higher resolution RS-2 Ultrafine data. In addition, we gained confidence in our method as the RS-2 U data had different radar geometry and a different acquisition date. There is, however, always room for improvement and in a revised version of this manuscript, we will include one more collected GPS track and field photographs from a third valley (Fig. 1b, Tamokdalen). This field photographs will come from a crowd-sourcing platform called regObs.no, which we will use to validate some more avalanches. We agree that the total amount of validation data is still insufficient to quantify the probability of correct/incorrect classification as well as the percentage of missing detections. We are only able to show, that we correctly detected avalanche debris in the valleys Breivikeidet and Lavangsdalen. The probabilities here (100% probability of correctly classification), gives us however, high

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confidence that our detection methodology works satisfactory all over the region. We moreover argue that we most likely miss some avalanches due to radar shadow and layover effects. For this purpose we show Figure 2c as an example for the limitations of our method.

3: "The manuscript does not report any substantial and new scientiïňAc results, thus failing to meet the basic requirement for research articles to be published in The Cryosphere". In our manuscript, we report two substantial and new scientific results, thus we clearly meet the requirements to publish in The Cryosphere: First, we report the use of Sentinel-1A data that become available two months prior to our analysis. Showing the usability of S1A data in avalanche detection is a large step towards operational use, as S1A data frequently covers large areas with high spatial resolution, on a worldwide basis. Moreover, the data is freely available. Long revisit intervals, small ground swaths, low spatial resolution, limited availability, and high costs limited previously the use of SAR data in avalanche detection. Second, to our best knowledge, space-borne SAR avalanche detection has not been shown in any peer-reviewed article yet. Only two conference proceedings show avalanche detection from SAR backscatter, using a handful of case studies. In this manuscript, however, we detect almost 500 features that we interpret as avalanche debris in an area covering 250 x 150 km. This is of great importance for operational avalanche forecasting in inaccessible mountain terrain. Moreover, this is clearly a first important step towards collecting a complete avalanche activity dataset from a defined region.

4: "It has been reported before that avalanche deposits can be detected in C-band SAR images due to increase of backscatter intensity. The manuscript does not provide any progress in this respect, neither describing the physical background for the observed signatures of avalanche deposits and surrounding terrain, nor presenting any objective method for detecting the avalanche debris." It is correct that space-borne SAR detection of avalanches utilizing increase in backscatter intensity is not new, and we do not claim that either. The methodology has, however, only been reported twice, in non-peer

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reviewed conference proceedings: (Wiesmann et al. 2001) and (Malnes et al. 2013). Both papers only describe single case studies of large avalanches. So from which scientific basis should we provide any progress? In truth, this manuscript for the first time puts space-borne SAR detection of avalanches to its intended use in covering a large area, and collecting spatially upscaled information of a phenomenon. On the physical background for the observed signatures: Section 1.1. addresses SAR backscatter theory and a brief literature review. We briefly discuss the main mechanisms involved (surface scatter from the roughness in the avalanche debris and volume scattering from the increased amount of snow). A full electromagnetic model for avalanche debris was not considered within the scope of this paper. The issue is certainly not well understood and should be studied in future. The parameterization of surfaces and snow volume in avalanche debris is however, very challenging to quantify. Electromagnetic modelling might also be challenging, with a large number of uncertain parameters (fine structure of surfaces, detailed knowledge about ice/snow blocks size, structure, permittivity, density etc.). We report on the effect we observe (increased backscatter from avalanche debris) and leave it to future studies to understand the physical mechanisms in detail. In a revised manuscript, we will provide basic statistics of backscatter values from all detected avalanches, comparing it to the backscatter values from undisturbed snow surrounding avalanches. We will furthermore use a topographic GIS model over the avalanche detections to distinguish avalanche from non-avalanche terrain. Both attempts should provide an assessment of the physical basis of using backscatter intensity, as well as a better quantification of correct detections.

5. "The procedure used by the authors for detecting the avalanche deposits is subjective image interpretation, lacking a sound and reproducible scientiïňAc basis." Our method is arguably subjective image interpretation. However, we provide validation data that makes us confident in our detections. We cannot think of any other phenomena that would cause such an increase in backscatter than avalanches. However, we see the need for providing better reproducible grounds of our work, which we will provide in a revised manuscript (see point 4). We also do not claim that the man-

ual detection method is flawless, and we thoroughly discuss its limitations. Automatic detection algorithms using e.g. threshold for backscatter increase have been tested. Unfortunately, they have to produce better results yet. The main problem we see is the heterogeneous increases in backscatter in the avalanche debris, limiting to date automatic detection.

6: "Besides, the analysis lacks comprehensive validation and deals with a single avalanche episode, not suitable for assessing the potential for operational applications addressed by the authors as a main motivation for this work." Reviewer 1 might not be familiar to the some of the major challenges of avalanche science, which this applied research article clearly addresses. We cite in our manuscript a recent ESA feasibility study (Bühler et al. 2014) were avalanche professionals stated their data needs. In summary, high spatial and temporal resolution data, with high confidence level and low acquisition costs were of interest and critical in providing better avalanche warning and forecasting. The report concludes that such data needs could as of 2014 not be satisfied. When analysing our S1A data, we concluded that a large step towards these data needs was possible to achieve, which motivated us to submit our manuscript.

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