Response to Anonymous Referee #1

We would like to thank the anonymous referee for the constructive comments and suggestions. We appreciate concise suggestions to improve the scientific contribution of our manuscript for The Cryosphere readers. We would also like to thank the referee for the provided references, which helped us to better understand the needs and concerns of the glaciologists working with the RES data interpretation

Hereby we provide the answer to the referee's response.

1 Answer to General Comments

Referee, General Comments: *In this manuscript, the authors present a novel radar focusing method that improves image quality based on the scattering properties of the ice surface, englacial reflectors, and ice bottom. This method can be used to improve the signal to noise ratio of englacial reflectors, can aid in the elimination of surface clutter and surface multiples, and can be used to diagnose the roughness characteristics of the surface and subsurface reflectors. The authors present the algorithm in sufficient detail to reproduce the results of their analysis, but the discussion of the* ***scientific*** *impact of the algorithm is limited – at present, this work is more appropriate for IEEE. To publish this work in The Cryosphere, the authors should include either (a) substantial discussion of the scientific utility of the new algorithm, or (b) more rigorous interpretation of their test data.*

Authors: We would like to stress, that the initial goal we've pursued in this paper was to provide glaciologists who use SAR RES data with a tool for analyzing angular scattering characteristics of the ice sheet and bed. The methods for improving the SNR of the internal layers and for mitigating surface multiples are provided as illustrative examples on how the knowledge of the aforementioned scattering characteristics can be utilized in practice.

The referee suggests two ways to improve the scientific of the publication. With regards to the second way ("more rigorous interpretation of their dataset"), in our opinion the restricted length and single flight direction configuration of the datasets analyzed is insufficient to provide a comprehensive glaciological interpretation of the scenes; additionally, our background is electrical engineering, and we do not posses sufficient expertise that would allow us to go a step further and provide a substantial glaciological interpretation of the datasets.

Thereby we would like to follow the first way ("substantial discussion of the scientific utility of the new algorithm") by including a discussion section on the scientific utility of the offered approach in a revised version of the manuscript (more on that in the last part of our response). By doing so, we hope that the revised version of the manuscript will contribute to the fruitful discussion between electrical engineers and the application scientists in glaciology.

2 Answer to Specific Comments

Referee, Specific Comments, paragraph 1: *The aims and scope of The Cryosphere sets standards for originality and impact of the published works. These are areas of weakness for the manuscript at present. Direction of arrival analysis is already well established in the literature (Al-Ibadi et al., 2017; Jezek et al., 2009; Wang et al., 2016). The authors do present a novel numerical scheme for inferring direction of arrival in the along-track direction. But their primary analysis is to show that englacial layers are more specular than the bed, and that deep layers are more conformal with the bed than shallow ones, two observations already discussed widely in the literature.*

Authors: We agree that the direction of arrival estimation (DOAE) is a well established technique in the field of RES of the terrestrial ice sheets. However, the papers cited by the referee have different objectives compared to ours and neither analyze nor directly address angular scattering characteristics of the ice sheet and bed. Al-Ibadi et al. (2017) apply a DOAE algorithm in the cross-track dimension in order to estimate the position of the bedrock scatters in the cross-track and after that generate a digital elevation model of the ice bottom. Jezek et al. (2009) offer a method that can be used to measure spatial reflectivity and 3-D surface and basal topography of the ice sheets; examples of the 3-D basal and bottom topographies are presented in the paper. Wang et al. (2016) discuss the development and performance of a new multichannel wideband radar for RES; a part of the processing chain for the radar includes use of DOAE in the cross-track dimension for surface clutter suppression and maximization of the signal's power coming from the nadir.

According to our knowledge and confirmed by the comment of the referee #2, so far a paper summarizing angular scattering properties of the ice sheet and bed is missing in the literature.

Referee, Specific Comments, paragraph 2: *There are few issues with the information presented, which makes this manuscript challenging to review. The authors cite (but do not pursue) two possible scientific applications* *of their method (1) to characterize bed roughness or subglacial hydrology (Schroeder et al., 2013) and (2) to better estimate layer slopes (Macgregor et al., 2015) and potentially relate those slopes to ice dynamics. To make this manuscript more appropriate in The Cryosphere, the authors could provide more substance in a number of ways: discuss the ice dynamic understanding derived from resolving steep englacial layers (Hindmarsh et al., 2006; Holschuh et al., 2017), spatially constrain the roughness characteristics in their test data and relate those to the underlying geology or ice flow behavior (Schroeder et al., 2014), or work toward a better understand the waveform characteristics of englacial reflectors (Drews et al., 2012) or diffuse scatterers (Jordan et al., 2017). Right now, the manuscript simply defines an algorithm and applies it there is essentially no interpretation of results. While the summary and conclusions might be interesting to radioglaciologists who regularly process radar data, they are unlikely to be interesting to radar-data end users or a general Cryosphere audience.*

Authors: In order to improve the scientific value of the manuscript for The Cryosphere readers, we would like to complement our paper with a discussion section on the scientific utility of the offered approach.

For the bed roughness characterization we plan to spatially constrain the bedrock response beamwidth in our datasets and compare the results with the roughness characteristic (specularity content) derived using the method presented by Schroeder et al. (2013).

Similarly, for the layer slope estimation we plan to compare the performance of our approach with at least one of the methods proposed by MacGregor et al. (2015), focusing on challenging areas where the slope of internal layers varies strongly in azimuth.

Additionally, we would also briefly discuss the other references provided by the reviewer.

Referee, Technical Corrections: *See the referee's comments.*

Authors: We agree with the need for the technical corrections suggested by the referee and will incorporate them into a revised version of the manuscript.

References

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