Response to comments of Reviewer 2 on manuscript tc-2021-358

We would like to thank Reviewer 2 for the peer-review, and for constructive comments and suggestions how to improve the paper. Furthermore, we thank Reviewer 2 for pointing to additional references for early experimental work regarding backscatter enhancement. Below we give a point-by-point reply to individual comments. The reviewer's comments are labeled as **RC#** and the corresponding author responses are labeled **A#**. Suggestions to change or add in the manuscript are written in blue color.

RC1: For Ku band volume scattering of snow, cross polarizations are usually strong. In laboratory experiments cross polarization enhancement are more conspicuous than co-polarization for both volume scattering (Kuga et al. JOSA A, 1985) and surface scattering (Johnson et al. IEEE Transactions on Antennas and Propagation 1994). What are the reasons for non-observations in this paper. How about deeper snow?

A1: In the reference Kuga et al. (1985), experimental data show (Figs. 2-4) that the co-polarized (CP) enhancement peak is more pronounced than the cross-polarized (XP) peak. Fig. 5, which shows a more pronounced XP peak, is a plot of a theoretical model, which doesn't seem to be experimentally validated. The authors themselves state that "It should be noted that Fig. 5 is obtained using the Rayleigh point-dipole model and cannot be compared quantitatively with the experimental results in which finite-sized particles are used." Furthermore, later theoretical references regarding CBOE (Mishchenko, 1992a, Figs. 3,4,12,13) as well as experiments (Wolf and Maret, 1985, Fig. 4) show that the co-polarized enhancement factor is larger than the cross-polarized enhancement factor (except extreme incidence angles very close to 90deg), and that with thicker samples, the co-polarized enhancements increases while the cross-polarized enhancment decreases and van Albada et al. (1987). The interpretation of the CBOE being caused by constructive interference of time-reversed pairs of electromagnetic wave paths also supports stronger intensities in the co-polarized channels, since if the incoming and returning waves have orthogonal polarizations, the time-reversal symmetry of the two opposing-direction paths is broken and constructive interference doesn't necessarily occur. We thus expected (and confirmed in preliminary analysis) that the cross-polarized enhancement peak is much smaller than the clearly pronounced co-polarized peak, despite volume scattering being the cause of its presence.

The enhancement peaks of rough surfaces experimentally observed by Johnson et al. (1996) in both co-polarized and cross-polarized channels appear to have half-width-at-half-maximum (HWHM) of at least 5–10 degrees, which is much larger than the characteristic peak width of the CBOE. Furthermore, the CBOE is not characteristic for surface scattering processes where low-order of scattering is much more likely. We thus postulate that the enhancement peaks observed by Johnson et al. (1996) are not caused by the CBOE, and thus no conclusions about the cross-polarized behaviour of the CBOE enhancement peaks observed in our experiment can be made from the referenced publication.

The reason for not including cross-pol KAPRI data in the results is the combination of the enhancement peak being less pronounced in the cross pol channels (as explained above), and the cross-pol data being much closer to the noise floor of the experiment. While it is true that – compared to other more surfaces-like media – snow is considered a medium where volume scattering is considerable, the cross-polarized channels still exhibit lower overall backscatter intensities than the co-polarized channels – e.g. in the experiments of King et al. (2015) the measured co-polarized σ_0 of snow at Ku-band varied between -13 and -5 dB, while the cross-polarized value varied between -26 and -15 dB. Furthermore, while the monostatic version of KAPRI offers in general very good SNR, the SNR of the bistatic experimental setup is reduced due to the necessity of using lower-gain horn antennas for reception. For the winter experiment, the SNR from the ROI for co-polarized channels for a single acquisition was estimated from the data as approximately 15 dB. For the cross-polarized channels, this was reduced to approximately 9 dB. Combined with the lower amplitude of the enhancement peak, and other sources of inaccuracy mentioned in Sect. 2.1.3, this was deemed too low to allow precise analysis of the existence of the peak and its properties, as noted on line 117.

Regarding deeper snow: Increasing the snow depth in our setting of 2 m of seasonal snow will likely exhibit diminishing effects on the observed cross- and co-pol backscatter because our retrieved scattering mean free path value of $\sim$40 cm suggests that most of the scattering occurs in the uppermost $\sim$2 m of the snow layer.

Future experiments aimed at acquisitions with increased SNR can indeed provide further insights based on analysis of cross-polarized channels, as we note in Section 4.4.

To consider the reviewer's comment, we suggest to add to the model section the following text: "Most CBOE models are based on scalar waves which do not consider the vector character of electromagnetic waves, i.e. their polarization. However, experimental and theoretical works show that CBOE occurs predominantly for co-polarized transmitted and received waves (VV and HH) where the model matches well experimental observation. They also show that CBOE for cross-polarized (VH) observations is significantly weaker and decreases with increasing sample thickness (van Albada et al., 1987; Mishchenko, 1992a,b; Wolf and Maret, 1985)."

To reiterate the point in the discussion we also suggest to add these references to line 526 which will then read: "In terms of polarimetric measurements, the results of this study, as well as experimental work and theoretical models (van Albada et al., 1987; Mishchenko, 1992a,b; Wolf and Maret, 1985), indicate that the effect is present predominantly in co-polarized channels, and the effect is equally strong at both horizontal and vertical polarizations."

To explain why we do not snow cross-pol observations for TanDEM-X, we suggest to add to the description of the Aletsch dataset in section 2.2.1: "At VH polarization no acquisitions at sufficiently large β were available."

RC2: The optical thickness can indicate the order of multiple scattering. Please discuss the optical thicknesses tau in the measurements at X band and Ku band.

A2: This is already discussed in the last paragraph of section 4.2.1 for Ku-band and in the second and third paragraph of section 4.2.2 even though the term "optical thickness" is not explicitly mentioned. In addition to (Van Der Mark et al., 1988) and (Van Albada et al., 1988) that are already referenced in our paper, we suggest to reference the work of Tsang and Ishimaru (1985) who modeled that the enhancement is decreased when the optical thickness $\tau = E\,d < 4$ with extinction coefficient E and sample thickness d. To address this, we suggest to add to section 4.2.1:

"Nevertheless, the optical thickness $\tau_d = E\,d \approx d/\Lambda_T$ of the snow depth d of only 3–4 scattering mean free paths Λ_T could limit higher order scattering. While Tsang and Ishimaru (1985) conclude that already at $\tau_d = 4$ models approximate well the half-space solution (where $\tau_d = \infty$), Van Der Mark et al. (1988, Figs. 9,12) show that the peak height and width, at least for very weakly absorbing media ($\Lambda_A \gg \Lambda_T$), might be affected up to $\tau_d \approx 30$."

and to write more clearly in Sect. 4.2.2: "On the tongue of Great Aletsch Glacier, where a seasonal snowpack is present during winter, no backscatter enhancement was observed in X-band (Fig. 9c). As seasonal snow is younger than multi-year firn, smaller snow grain sizes are expected, resulting in scattering lengths larger than the value $\Lambda_T = 2.1$ m determined for the accumulation area. The thickness of the seasonal snowpack of 0–3 m corresponds therefore to an optical thickness $\tau_d \approx 1$ or less, which considerably affects the peak intensity (Van Der Mark et al., 1988, Fig. 9). In consequence, the single scattering at the (possibly rough) snow-ice interface at the bottom of the snowpack can remain the dominant scattering process. The low average number of scattering events in the seasonal snow volume is, therefore, not sufficient for the CBOE to occur on the ablation area of Great Aletsch Glacier. "

In the new section about limitations of the model (see comments to Reviewer 1), we suggest to address the limited optical thickness of the snow pack again and will write: "An additional limitation for a accurate estimation of Λ_A, possibly also Λ_T, results from the assumption that the scattering medium fills a semi-infinite space whereas the snow pack has a limited optical thickness τ_d. Hence, Λ_A might be underestimated due to limited layer thickness (Van Der Mark et al., 1988; Van Albada et al., 1988)."

RC3: For X band at Tandem X, the soil surface below the snow have significant contributions. What is the magnitude of surface scattering of the snow/soil interface below the snow layer?

A3: Comparing the scattering mean free path at X-band (here: 1-3 meters) with the typical snow height in the Swiss Alps in winter ($\sim 1-4\,\mathrm{m}$) indicates that there must be a strong contribution (likely more than 50%) from the ground, at least for snow over ground or snow over ice. This is discussed already in section 4.2.2 (with a modification proposed in **A2**): "In consequence, the single scattering at the (possibly rough) snow-ice interface at the bottom of the snowpack can remain the dominant scattering process."

RC4 Will there be coherent backscattering due to rough soil surface below the snow at X band?

A4: As indicated in Fig. 9 (and also Fig. 11), and as discussed in section 4.2.2 (Satellite observations - TanDEM-X) we did not observe any coherent backscatter from areas different than the high accumulation area of glaciers. Specifically, Figure 9 shows the dependence of the bistatic-to-monostatic backscatter ratio for different areas (high accumulation area, glacier ablation zone, conifer forest). Figure 9c for the glacier ablation zone, where 2-4 meters of snow cover the rough ice surface, does not show any signal of coherent backscatter enhancement. To make this explicitly clear, we suggest to add "We also did not observe coherent backscatter enhancement in any area other than the high accumulation area, even though the tongue of Aletsch glacier is highly crevassed and valley slopes are covered by rock debris. From this we conclude that in the X-band, rough surfaces do not elicit the CBOE." at the end of section 4.2.2.

References

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