***Comment on* "Review Article: Global Monitoring of Snow Water Equivalent using High Frequency Radar Remote Sensing" by L. Tsang et al.**

General Comments:

In this manuscript the authors present a comprehensive review on methods and experimental studies for snow water equivalent (SWE) measurement by means of radar-based remote sensing techniques with the focus on radar systems operating at Ku-band and X-band frequencies. A main motivation for the review is the preparation for a future satellite mission for measuring SWE, in order to close a main gap in the observation of key parameters of the global climate system. The manuscript is generally well written, comprising many technical details. According to the layout and contents it addresses primarily remote sensing experts. Some of the references are of marginal relevance for the topic of the review, in particular several of those that are reporting on studies related to vegetation. The readability would benefit from some cutback in this respect in order to improve the focus on the main issues.

For the wider snow research and monitoring communities it may be difficult capturing distinct information on the suitability of methods and tools that are relevant for their specific application. To this end a clear assessment of the performance and constraints of current methods and tools is needed, as well as a discussion how errors and uncertainties may impact the retrieval accuracy. It is also necessary to point out that by now the retrievals are relying on a few limited test cases, making the performance of models and algorithms for general application hard to assess. Furthermore, for some of the subtopics a sound description is. For these cases (in particular Sect. 5.2 and 5.3) I recommended major shortening as they are not of direct relevance for the main topic of the manuscript. Please find below details on my concerns and recommendations for revisions.

Specific Comments:

References on scientific and technical activities for the ESA Earth Explorer candidate mission CoReH2O:
In several sections of the manuscript reference is made to the CoReH2O mission. However, the references do not proceed beyond the statues of Phase 0 (first assessment studies). The Phase 0 activities were succeeded by detailed scientific and technical feasibility studies (Phase A), results of which are summarized in the (public) Report for Mission Selection (ESA, 2012). Apart from scientific and technical details, this document reports also results of performance studies and points out critical areas and risks, issues that are still of relevance and should be addressed in the review.

L87: The claim for a "dramatic" advancement of radar retrieval algorithms is not based on actual evidence. There is not yet any generally applicable and widely tested algorithm available for SWE retrieval. The proposed algorithms (Section 4) apply still the basic approach proposed for the CoReH2O mission that is based on constrained minimization in which iteration is performed for two free variables, SWE and a parameter related to the volume scattering albedo (ESA, 2012). By now the retrievals are relying on - and have been optimized for - a few test cases. See also the comment on Sect. 4.1 and 4.2 below.

L96: Please provide a reference to studies or documents specifying the spatial and temporal requirements.

L107: In mountain areas the spatial variability of SWE is below 100 m. See e.g. Grünewald et al., 2010.

L162: "volume scattering increases with snow mass" This is a cursory statement, not accounting for other factors that affect and may dominate the volume scattering signal.

L176, Fig. 1: Ground-volume interactions are missing.

L225, Fig. 3 and related text: Structural anisotropy is a characteristic feature of natural snow packs (e.g. Leinss et al., 2020). This causes changes of the phase matrix with the incidence angle. Please explain in which way incidence angle effects related to structural anisotropy are taken into account in the models for computing radar signal propagation and phase matrix.

L257, Fig. 4 and related text: This example is based on a very limited data base, comprising only three points out of daily NoSRex SnowScat measurements that were acquired during four winter seasons with quite different backscatter behaviour (Lemmetyinen et al., 2014; 2016). For comprehensive evaluation of the model a wider view is needed, checking data at different incidence angles and for cases with different snow structural properties. If such an analysis is not available, current limitations in this respect need to be addressed.

L288, Fig. 5(a): Is there any particular reason why different rms heights are used for wet and frozen soil?

L322, Fig. 6(a): The sample of 5 points, 4 of which show the same moisture value, is not an adequate sample for a reliable performance estimate of the soil moisture retrieval algorithm. Fig 6(b) shows also a very small sample, not matching the needs for statistically significant performance estimates. Computations at different incidence angles and comparisons with experimental data (as available from NoSRex) would provide higher confidence. Furthermore, please specify the incidence angle and the state of the soil in Fig. 6(b). Please check the allocation of the blue and red marks in the figure caption; it seems the symbols for NoSREx and SnowEx have been mixed up.

L347ff, impact of forests: Here it should also be mentioned that in CoReH2O Phase A the impact of forests on radar signals of snow covered ground was studied (ESA, 2012), described in detail by Montomoli et al. (2016). The forest model selected for this study accounts for scattering of trunks, branches of different size and needles, as well as for differences in the structure of vertical layers. Effects of differences in cover fraction, tree height and biomass were analysed. Consequently, this model allows for a multifaceted description of forest properties and for estimating the impact of the forest parameters on the backscatter of snow covered forests.

L415, Fig.9: Reference to scattering and penetration of wheat canopies is of marginal relevance for snow studies. This should better be replaced by results from studies concerned with forest canopies.

L425ff: The radar penetration capability in forests depends on the density and structure of the canopy and on dielectric properties. Rather than referring to lidar observations, reference should be made to studies on radar signal penetration. Kugler et al. (2014) show for various forest canopies (including coniferous) that the X-band scattering phase centre height is located well above the ground surface and the ground scattering contribution is marginal. A reasonable extrapolation from X-band to Ku-band should be possible.

L487: Please provide specifications on properties of the Ku-band SAR or a reference.

L508, Table 3, Row 3: Dates for SnowSAR campaign Finland need to be corrected: March 2011 and winter 2011-2012.

L524ff, Section 3.3.1, field measurements: This section presents a specific, detailed proposal on arrangement and techniques of field measurements, in its content not directly related to the topic of the review. It should better be provided as Supplement or moved to the Appendix.

Besides, the proposed arrangement requires special tools and would not be applicable on any type of terrain. In practice a trade-off between available resources and spatial coverage is needed.

L628ff, Sections 4.1 and 4.2 (on the retrieval problem and need for a priori information): The example algorithms apply the same basic approach as proposed for the CoReH2O mission, based on constrained minimization in which iteration is performed for two free variables, SWE and a parameter effective grain size related to the volume scattering albedo (ESA, 2012). Whereas the CoReH2O baseline version accounts for backscatter data from four channels (X-and Ku-band co- and cross-polarization) the algorithm specified in Equ. 3 uses backscatter from two channels (co-polarized) and iterates also for two free variables: total optical thickness (related to SWE after eliminating the scattering contributions) and scattering albedo (which was used as one of the free variables in the retrieval version of the CoReH2O Phase-0 studies). A critical issue is the need for accurate a priori estimates on snowpack physical properties as input for the configuration parameters of the backscatter forward model as well as for regularization. Of main concern is the parameter for describing the scattering properties (related to microstructure) for which a priori estimates within a small error bound are needed. In the performance study for CoReH2O Level-2 products the accuracy requirements of a priori data for model configuration and regularisation were quantified (ESA, 2012). This was a limited first effort. A wider view is needed for quantifying the impact of uncertainty in a priori estimates on retrieval accuracy for the different states of the global snow cover. Though addressed here between the lines, definite numbers on a priori data requirements would be needed for full traceability.

L666, Table 4: The generic information on typical properties of snow types in Alaska, provided in this table, is not a suitable a-priori input on snow properties, as required for inversion model initialization and regularization. This comment refers not only to specifications such as “no data” or “variable”, or the contents of the last column (e.g. quoting new and wet snow for characterizing the maritime snow class), etc.

L715: Huang et al. (2012) refer to scattering of rough soil surfaces and not to snow.

L775, L776: The publications of Lemmetyinen et al. and Zhu et al. confirm the importance of reliable a priori estimates on snow microstructure (in line with the comments above on Sections 4.1 and 4.2). In these cases site-specific approaches are used for estimating snow structural parameters. In its core these retrieval algorithms (applying constrained minimization) are the same as proposed for CoReH2O and tested in the Mission Phase A with SnowScat data (ESA, 2012) and in follow-up activities with SnowSAR data (e.g. Rott et al., 2013). I was not able to locate the publication of King et al. (2019) that is cited in L776 and addressed in L784 to L790.

L853: Please explain the link between the co-located ground measurements and the derived a priori information.

L888: Please provide a reference on the difference in saturation between the co- and cross-polarized signals. NoSRex Snowscat data show similar sensitivity in terms of SWE for co- and cross-polarized Ku-band data (e.g. Lemmetyinen et al., 2014), suggesting a similar saturation limit.

L931ff, Section 5.2, C-band: This contribution is problematic as it provides a biased view. It expands on the statement “the volume scattering by snow grains was believed to be small at C-band” (L935). Rather than guesswork, the knowledge on C-band radar wave interaction with snow is based on careful theoretical and experimental work over years, confirming the prevalence of low backscatter intensity for seasonal snow in mountain areas. References to such studies are needed for a balanced account. Besides, the notes on some of the papers cited in this section are questionable. For example, Pivot et al. (2012) show little change of Radarsat sigma-0 during the main part of the snow cover season (Nov. to April) at the six test sites, intermittently even a drop. Shi et al. (2000) is not included in the list of references. The data presented by Arslan et al. (2006) show similar change in in co- and cross-polarized sigma-0. There is not any statistically significant difference in the relation between either C-VV or C-VH and SWE. Bernier et al. (1999) did not use any cross-pol data. They show that C-band sigma-0 decreases with increasing SWE due to change of the backscatter contribution from ground. The Sect. 5.2 conveys the message that snow microstructure and properties of the underlying ground are of no relevance for C-band cross-polarized backscatter, in contradiction to the detailed description of the related processes in Sect. 3. Clarifying this apparent contradiction would warrant a separate publication. Therefore Sect. 5.2 should be scaled down down to a summary with some references.

L1007: McGrawth et al. (2019) report on GPR measurement of snow depth only.

L1027 and Fig. 17: Please provide information on the sensor and measurement site.

L1035, Section 5.3.3, Interferometry: The method of repeat-pass InSAR for SWE retrieval and related experiments have been described in several publications. This section does not provide any new insights and contains some errors. Therefore it is recommended to shorten this section significantly. A short summary and some key references will do. The method exploiting the phase delay in snow traces back to Guneriussen et al. (2001), not to the references cited in L1038. Further issues: L1049: SWE measurements by means of phase delay in repeat-pass InSAR do not require a second antenna. Zero baseline is optimum; in this case there is problem of ambiguity with the topographic phase is avoided. Fig. 18a: The plot and the equation are incorrect; the geometric relations are neglected. Also, it is unclear to which measurement principle the figure refers. Probably it should indicate the measurement of snow surface height by DEM differencing which can be applied in case of surface scattering (wet snow) and requires requiring single-pass InSAR. L1072ff: The paragraph on the scattering phase centre in snow is rather speculative, references report on vegetation studies, the specific conditions of interferometric radar signal propagation in snow are not taken into account (e.g. Dall, 2007). The position of the scattering phase centre in snow volumes is highly dependent snow microstructure, obscuring possible relations with snow mass (e.g. Rott et al., 2021).

L1150: Please provide a reference on the direct assimilation of Ku-band backscatter intensity in snow process models. The statement here, claiming that this can be done, needs a proof.

L1174ff, Summary and Perspectives: This review shows that significant advancements have been achieved in the fields of radar signal propagation, snow microstructure observations and backscatter modelling. On the other hand, the retrieval algorithms are still based on the same concept developed for the CoReH2O mission that requires a priori information on snow properties within comparatively narrow error bars. Major progress has been achieved in deriving such information from various sources, however by now optimized for local retrievals and tested with few confined data sets. The wider applicability and performance need to be proven. The perspectives quoted in this section are limited to short unspecific statements. Details on plans for further development would be of interest.

List of references: Please check the alphabetic order.

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