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The Cryosphere Discussions
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Interactive comment on "3D-VAR multilayer assimilation of X-band SAR data into a detailed snowpack model" *by* X. V. Phan et al.

Anonymous Referee #3

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This study presents methods to incorporate satellite synthetic aperture radar (SAR) observations using data assimilation techniques into snowpack modeling. The goal of this work is to better simulate snowpack physical and stratigraphic properties using SAR backscatter, which is sensitive to snow/ice characteristics. The presented approach first derives snowpack properties (density and grain size) using a reanalysis-driven multilayer snow model, Crocus. These modeled snowpack properties are then used as input to an electromagnetic backscattering model (EBM) based on dense media radiative transfer theory in order to simulate backscattering from the snowpack. This first process can be thought of as a control run that takes only the reanalysis (SAFRAN) meteorological conditions as input. Next, on the Argentière Glacier in the French Alps, the authors employ a minimization approach (3DVAR) in order to reduce discrepancies between observed SAR backscatter and that simulated by the EBM by modifying

snowpack physical properties within Crocus during satellite overpasses (each 11 days). Using the modified (i.e., SAR-informed) snowpack properties, Crocus is then rerun as input to the EBM to re-simulate snowpack backscattering. The authors find that this SAR-assimilated modeled backscatter is in good agreement with the observed SAR backscatter.

These novel methods are of potential interest and utility to the remote sensing, snowpack modeling, and cryospheric communities. Indeed, incorporating SAR observations into snowpack models for data sparse alpine (and polar) regions is a worthwhile endeavor and may lead to inversion techniques to derive detailed snowpack characteristics from remote sensing. For these reasons, I feel the manuscript is topically suited for publication in The Cryosphere.

The paper could be improved in several key regards to improve clarity and establish the robustness of the results. I suggest that some reorganization and rewriting is warranted, particularly in the introduction and conclusions sections. Many comments to this end are noted below, although my list is not entirely exhaustive. For example, there is some redundancy between the introduction and methods sections, and the motivation for the study is not very well established in the introduction.

More substantially, there is no quantification to the improvement to simulating snowpack backscattering and derivation of physical properties using the presented methods. Without quantifying differences between various methods presented in this paper, it is unclear if assimilating SAR-observed backscatter into snowpack models provides better results. Also, the prescribed snowpack properties need to be justified and discrepancies between the text and figures regarding data availability and use (or perhaps exclusion) needs to be explained. Furthermore, no ground truthing is presented in this study; rather it is left as a potential future endeavor. This is despite the apparent availability of in situ observations as stated in the acknowledgements section and presented by the authors previously (Phan, et al (2012), Multilayer snowpack backscattering model and assimilation of TerraSAR-X satellite data, in Geoscience and Remote

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Sensing Symposium (IGARSS), 2012 IEEE International, pp. 5856–5859). An important question therefore persists: does Crocus driven by observed (or reanalysis) meteorological variables perform better than a SAR-assimilated Crocus? If not, why should SAR data be assimilated into snowpack models?

I understand the following list of comments may seem overwhelming, but most are suggestions for relatively minor changes to wording and advice to improve the overall clarity of the paper. Some more major issues exist with the study that I feel warrant addressing. Nevertheless, I encourage the authors to consider these suggestions for revision as I feel there is promise in the presented techniques in improving our understanding of snowpack evolution and monitoring.

General comments:

1. It is unclear what SAR image acquisitions are used in the study. There are discrepancies between the text, Table 1, and figures indicating some data were not used in certain parts of the analysis. If certain data were excluded, this should be made clear and the impacts on the assimilation process and Crocus snowpack evolution explained. Please see the specific comments on this for page 4894.

2. Some justification is needed for the choice of snowpack parameters in the sensitivity analysis (section 4.3). In particular, grain sizes used are quite large (0.5-1mm) and roughness values describing the correlation length and rms height are taken from a study examining these parameters for bare soil, not snow/ice surfaces. Please also see specific comments for page 4895.

3. The results from this study need to be better contextualized with the existing literature. Much work has been performed on assessing snowpack properties from radar observations. How are the techniques presented here advancing this knowledge? This should be included in the results/discussion or conclusions section.

4. Figures 1 and 2 are taken from other studies. At minimum, this should be made clear

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in the figure captions. E.g., Figure adapted/used from xxxxx (20xx) with permission.

5. The overall importance or relevance of SAR assimilation into snowpack models is not made very clear. The introduction section could more directly identify existing knowledge gaps/limitations (i.e., few in situ observations exist necessary to evaluate, inform, and adjust snowpack models... which are critical for snow cover forecasting, water resource monitoring, and avalanche prediction) and the provided value/contribution of this study (SAR observations may potentially be incorporated into snow models, thus improving confidence in their results!). Without revision here, the purpose of the study remains somewhat ambiguous.

6. The introduction section would benefit from reorganization and revision. The first paragraph gives the problem statement, which concludes on the general techniques employed in the study. In particular, the techniques could be more explicitly stated and summarized (the backscattering model, SAR platform, and snowpack model should all be introduced in (or near) the first paragraph with note that they are more thoroughly introduced in the following paragraphs and/or the methods section). Here, referencing Figure 3 (which is incredibly useful!), would be ideal. I suggest the authors consider moving Figure 3 to become Figure 1. Otherwise, the reader is tasked with attempting to visualize this flow chart without knowing that it later depicted as a figure!

7. Snowpack modeling is mentioned throughout the introduction section, but not in the first paragraph (as the other methods are noted). Further, the specific model used (Crocus) or how these models function is nowhere stated in the introduction (as the EBM and assimilation techniques are explained). I would suggest the authors explicitly state within the first paragraph that this study uses TerraSAR-X, Crocus, an EBM, and assimilation techniques. Then, in the following introduction paragraph(s), briefly introduce each method and their context with relevant studies. I suggest considering scaling back methods details within the introduction section. Much material is presented here that is later repeated in the methods sections. Instead, I would suggest synthesizing this content into one or two sentences for each method and then put this

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into in a single paragraph in which you describe the overall method of the paper (and reference the flow chart figure 3). As a potential problem for the current layout, “guess” variables/parameters and “the analysis” are defined in the introduction (p 4884 lines 4-5) and then referred to in the methods section (p 4892 line 23). Readers unfamiliar with this terminology may get confused and need to flip back to the introduction to get their definitions.

8. Along the same lines, the difference between open loop and closed loop Crocus runs needs to be better explained. Only is the open loop method (i.e., without any SAR assimilation) defined in the text. It should be made clear in the text that “closed loop” is the same as the “analysed” situation (i.e., with SAR basckscatter assimilation), if I am understanding this correctly. As it stands, the reader is left to decipher the differences. Please use a consistent terminology for the different model cases throughout the paper text and figures. These different model setup scenarios need to be made clear. Perhaps consider adding a table to define the cases (guessed/Crocus, analysed/closed-loop/SAR-assimulated, open-loop Crocus). Alternatively, Figure 3 could be updated showing the different experimental setups.

9. While EBM-produced and SAR-observed backscatter are in better agreement, it remains unclear to what extent the snowpack is better represented (i.e., the overarching goal of the study) without in situ validation. Furthermore, there is no attempt to quantify the differences between observed backscatter and that modeled by Crocus (with and without assimilation). This is critical, as it is unclear which method (Crocus with “guessed” profiles, EBM “analysed” profiles (aka closed loop), or the Crocus “open-loop” profiles (without assimilation) works best or if there is any real (statistical) difference between the methods. Which best matches the observed backscatter? How does this vary over space and time? I feel this needs to be quantified.

10. In figure 9 it is clear that the guessed and analysed profiles are nearly identical, whereas the open-loop profile does not match the other two. My understanding is that the dark blue lines (guessed profile) is from the SAFRAN-forced Crocus input

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into the EBM, whereas the green (analysed) profiles then incorporate the SAR data in the assimilation method to modify snowpack properties in Crocus. If this is the case, and there is little to no difference between modeled and SAR-incorporated snowpack parameters, then what is the value of the whole method of assimilating SAR observations?

Specific comments:

1. P. 4882 Line 2: Replace “structure” with “physical”

2. P. 4882 Line 6: Change to “These snowpack properties”

3. P. 4882 Line 8: Replace “calculates the simulated” with “simulates”

4. P. 4882 Line 12: Replace “structure” with “physical”

5. P. 4882 Line 14: Replace “has” with “have”

6. P. 4882 Lines 14-16: “Show the high potential of this method for improving snow cover simulation” needs to be more specific.

7. P. 4882 Line 18: Replace “essential” with “critical”

8. P. 4882 Line 19: Replace “its” with “snowpack”

9. P. 4882 Line 19: Insert comma after “over time”

10. P. 4882 Line 19: Replace “provides greater benefit” with “is essential”

11. P. 4882 Line 20: Replace “snow avalanches warning” with “avalanche warning” 12. P. 4882 Line 21: Could insert mention of Crocus here “. . . snowpack evolution models, such as Crocus (ref), are developed. . .”

13. P. 4882 Line 23: Move “in situ” to before “snow”

14. P. 4882 Line 23: Explain how/why the models are limited. Sparse meteorological observations exist necessary to drive the models (thus requiring reanalysis use) and

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in situ snowpack observations are likewise lacking, which are necessary to evaluate model output and adjust their physics. If you make this statement more forceful, the impetus for the study is far more compelling. This is something that the SAR data can be of potentially critical importance to addressing these present deficiencies.

15. P. 4882 Lines 23-25: Please be more specific about the "new generation" of SAR platforms. Perhaps it's best to specifically mention TerraSAR-X. You could also start this sentence off with, "Addressing these observational deficiencies are new SAR platforms. . ." or end the sentence with why we would want to assimilate SAR data into snowpack models. . . "with the goal of increasing accuracy and confidence in snowpack modeling results." Without some revision here, the purpose of the study is not very clear.

16. P. 4883 Line 1: Insert "(backscatter)" after "reflectivity"

17. P. 4883 Line 1: Replace "analyze" with "evaluate"

18. P. 4883 Line 1: "Replace "calculated" with "simulated"

19. P. 4883 Line 2: Remove "these"

20. P. 4883 Line 2: Replace "values" with "snowpack properties"

21. P. 4883 Line 11: Replace "model" with "EBM"

22. P. 4883 Line 15: Replace "strong variations of various" with "highly variable"

23. P. 4883 Line 16: Explain thickness, i.e., you are talking about snowpack layer thicknesses.

24. P. 4883 Line 19: Replace "cover maps" with "mapping"

25. P. 4883 Line 20: Explain "inversing the physical models" – You mean inverting electromagnetic backscattering models, right?

26. P. 4883 Line 21: Insert "snowpack" before "properties"

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27. P. 4883 Line 26: Replace “meteorology” with “meteorological”

28. P. 4883 Line 27: Insert “and” before “land”

29. P. 4883 Line 28: Multilayer is one word

30. P. 4883 Line 29: Replace “, related to snow” with “utilizing”

31. P. 4884 Line 1: replace “or” with “and”

32. P. 4884 Line 1: Replace “assimilation” with “observations”

33. P. 4884 Lines 1-3: Consider changing to “Such assimilation techniques have proven effective in combining observations and a priori information to more realistically simulate snowpack conditions (i.e., an a posteriori state). “

34. P. 4884 Line 4: Put “guess parameters” in quotes

35. P. 4884 Line 5: Put “the analysis” in quotes.

36. P. 4884 Line 6: “the snow evolution model” is not yet defined. Please change to “a snow evolution (or snowpack) model”

37. P. 4884 Lines 11-12: “which allows to constrain” is unclear. Perhaps change to “permits informing snowpack simulation using. . .”

38. P. 4884 Paragraph starting on line 13: It would be good to introduce the different model scenarios here (see general comments 4 and 5) or elsewhere in the introduction. Please also consider referencing Figure 3 (move to Figure 1) somewhere in the introduction – either in this paragraph or earlier.

39. P. 4884 Line 14: Replace “The” with “A”

40. P. 4885 Line 1: EWM is not defined. Please define or change to “Electromagnetic”

41. P. 4885 Line 17: RT is not defined. Please define as “radiative transfer (RT)”

42. P. 4885 Line 17: Remove “at order 1” and begin sentence with “The first order

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solution of the radiative transfer (RT) equation. . .”

43. P. 4885 Line 17: Replace “a total” with “the total”

44. P. 4886 Line 2: Replace “over” with “from”

45. P. 4886 Line 2: Replace “ground” with “snow-ground interface” 46. P. 4886 Lines 2-3: Reference abbreviations used in the figure

47. P. 4886 Line 9: Change “Fung et al. (Fung and Chen, 2004)” to “Fung and Chen (2004)”

48. P. 4886 Lines 21-22: Change “(Fung and Chen, 2004)” to “Fung and Chen (2004)”

49. P. 4887 Lines 9-10: Replace “strong variations of various” with “strongly variable”

50. P. 4887 Line 17: Correct reference style as before.

51. P. 4887 Line 17: Replace “such medium” with “such a medium” or “media”

52. P. 4887 Line 18: Change “effect” to “effects”

53. P. 4889 Line 11: Add “(attenuation)” after “intensity loss”

54. P. 4890 Line 2: Add reference to figure 1 after “the thickness of layer k”

55. P. 4891 Line 4: Change “are” to “can be” or alternatively, change the sentence to state, “In this study within the French Alps, these meteorological conditions are taken from the SAFRAN reanalysis, which combines. . .”

56. P. 4891 Line 5: Change “radioprobes” with “radiosondes”

57. P. 4891 Line 11-12: Replace the ellipses “. . . “ to “etc.”

58. P. 4891 Line 18: Replace “observation” with “observational”

59. P. 4891 Line 21: Change to “searching for a solution”

60. P. 4892 Line 13: Put R in parentheses, “(R)”

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61. P. 4892 Line 13: Change to “of the model (B; i.e., the guess error covariance).”

62. P. 4893 Line 5: Replace “of natural” to “of a natural”

63. P. 4893 Line 5: Change “by a specific” to “by specific”

64. P. 4893 Line 10: Add “a” to “in the case of a snowpack. . .”

65. P. 4893 Line 14: Awkward/spelling error. Consider changing “ill-conditioned and practically pointless” to “impractical”

66. P. 4893 Line 16: Unclear, please explain “allowing to add an a priori information”

67. P. 4893 Line 17: Change “as guess” to “as guess variables”

68. P. 4893 Line 19: Change “guess” to “guess variables”

69. P. 4894 Line 3: Change “on” to “in”

70. P. 4894 Line 4: What SAR data were used/analyzed? Table 1 only specifies three dates in March. The text here suggests availability of 8 images (11 day repeat, starting on 6 January and ending 24 March). Perhaps more importantly, it appears that at least one day (28 January) is completely excluded from the analysis. For example, both 28-Jan and 2-Mar are missing in Figure 5. Six points at each elevation in Figure 6 suggests these days are also excluded here. Both Figures 8 and 9 include 2-March, however. Please explain if these data do not exist, which images are used in each part of the study, and if and why some images were excluded from the analysis. Also, if data were excluded, how does the assimilation process and Crocus deal with missing a time step?

71. P. 4894 Line 5: Change to “Table 1 shows”

72. P. 4894 Line 16: Change to “a Frost filter”

73. P. 4894 Line 17: Change to “at an altitude of 2700 m”

74. P. 4894 Line 19: Change to “triangles”

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75. P. 4894 Line 20: Change to “circles”

76. P. 4894 Line 21: change to “decreased between successive observations”

77. P. 4894 Line 22: Change to “crosses”

78. P. 4894 Line 25: Can you speculate on the physical processes occurring to the snowpack? Is heavy snow accumulation causing backscatter attenuation (or increased volume scattering?) versus compaction/densification causing increased surface scattering? What does SAFRAN and Crocus indicate is occurring between these periods? Was there an episode of melt and refreeze that caused increased surface scattering perhaps?

79. P. 4895 Line 3: Change “consists of the number” to “consists of a number”

80. P. 4895 Line 7: Place tau in parentheses.

81. P. 4895 Line 11: Correct spelling of permittivity

82. P. 4895 Line 11: Remove “is” before “largely”

83. P. 4895 Line 13: Please explain “vertical profile description” – perhaps change to “snowpack stratigraphy”

84. P. 4895 Line 14: Correct spelling of “sensitivity”

85. P. 4895 Line 17: as on line 14

86. P. 4895 Line 18-19: Change to “A random dataset was generated corresponding to . . .”

87. P. 4895 Line 21: 0.5 mm is not a “small” particle size particularly for fresh snow (e.g., Jin et al., 2008, Remote Sensing of Environment; Painter et al., 2007, Journal of Glaciology). Conversely, 1 mm is quite large.

88. P. 4895 Line 23: Oh et al. (1992) presents roughness observations for bare soil. Some justification is needed for use of these values, particularly given that roughness

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parameters have been widely measured across snow and glacial surfaces. For example, please see Lacroix et al. (2008, Journal of Glaciology), where these parameters are measured and compared for different regions. Also, the glacier (snow-ice interface) roughness values stated in the text do not match those stated in the caption for figure 7. Please double-check these numbers.

89. P. 4896 Lines 4-6. Awkward sentence, please rewrite. Also, it is not clear to me (as stated in the text here) that above 500 mm SWE ground backscattering is "considerably" lower than volume backscattering. I see that ground backscatter has less variance than volume scattering, that ground backscattering is higher than volume at SWE<∼350mm, and that around 700mm SWE ground and volume scattering appear equal (at least the means). Perhaps these are my misinterpretations, but maybe the figure could be improved by adding an indication of point density and/or lines showing the mean backscatter components across different snowpack SWEs. Again, parameters for this sensitivity test should be examined.

90. P. 4896 Line 16: Change to "At the first iteration . . ."

91. P. 4896 Lines 17-18: It would be good to remind the reader what the guess variable is here.

92. P. 4897 Line 1: Replace "are" with "is"

93. P. 4897 Line 5: Replace "splitted" with "split"

94. P. 4897 Line 9: Remove ", i.e."

95. P. 4897 Line 10: Replace "differences in" with "varying"

96. P. 4897 Line 10: remove comma after "inputs"

97. P. 4897 Line 11: Replace "have been" with "were"

98. P. 4897 Line 17: same as line 11

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99. P. 4897 Line 19: Change to “times and locations”

100. P. 4897 Line 19: Replace “experiment” with “analysis”

101. P. 4897 Line 19: Change “percent” to “%”

102. P. 4897 Line 22: Change “two” to “three”

103. P. 4897 Line 23: Change to “2600 m elevation”

104. P. 4898 Lines 1-5 (and lines 24-26 on previous page): All of this material seems best suited for the figure caption.

105. P. 4898 Lines 10-12: This sentence is awkward

106. P. 4898 Line 33-34: Please define the open and closed loop scenarios, and use “closed” instead of “close loop”

107. P. 4898 Line 26: Change “difference” to “different”

108. P. 4899 Line 2: Please better define “data analysis method”

109. P. 4899 Line 9: “shows interesting results” is too vague of a conclusion. Please quantify the effects of using the assimilation of observed SAR into the backscatter model. Do we get a more realistic snowpack?

110. Table 1: The acquisition dates and data used in this study need to be explained (see previous comments to this effect). Add in line for the repeat time (11 days).

111. Figure 1: This figure is taken from Longepe et al. (2009; IEEE Remote Sensing) and should be acknowledged as such. Please define at least k and the incidence angle here in the figure caption. Why not just create a new figure though with only the terms important to this study? In this situation, soil could be change to glacier.

112. Figure 2: This figure is taken from Vionnet et al. (2012; Geosci. Model Dev.) and should be acknowledged as such. It is also unclear whether the figure is actually needed in this paper.

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113. Figure 3: Good figure. Do the text colors match up with the later figures? Perhaps consider adding the different model setups to make it clear which configuration was used in the different experiments (i.e., with/without 3DVAR, open loop, etc.).

114. Figure 4: Change “will be used in the case study” to “was used. . .” Perhaps also add labels for each box (A,B,C. . .)

115. Figure 5: Should dates be in Year-month-day format as in the rest of the paper? Where are the missing dates? Change “of winter season” to “in the winter season of”. After 2008-2009 add “at an altitude of . . .”

116. Figure 7: Roughness parameters stated here differ from those in the text. Which were used?

117. Figure 8: Correct spelling of “crevassed” and “position” on each plot. Please also better describe each scenario shown – presently, the differences between various scenarios is not clear. The dark blue triangles are also not described in the caption. Please note the red line is observed from SAR.

Interactive comment on The Cryosphere Discuss., 7, 4881, 2013.