

Interactive comment on “Seasonal variations of the backscattering coefficient measured by radar altimeters over the Antarctica Ice Sheet” by Fifi I. Adodo et al.

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Interactive comment on “Seasonal variations of the backscattering coefficient measured by radar altimeters over the Antarctica Ice Sheet” by Fifi I. Adodo et al.

The authors have in this study analyzed seasonal variations in observed radar backscatter over the Antarctic ice sheet from two different altimetry missions spanning three different frequency bands (S, Ku, Ka). They identify two clearly marked zones over the continent exhibiting different and common frequency dependent characteristic. Exemplified, with a peak in backscattered power in the summer for the S-band, in winter for the Ka-band and for both winter and summer in the Ku-band. They attribute

C1

the difference in the observed radar backscatter to the different bands sensitivity to volume/surface scattering. To quantify the governing parameters in the snow-properties at each frequency a sensitivity study was undertaken, which took into account the snow density, grain size and snow temperature using an electromagnetic model. I find the contribution of the paper timely and interesting, as many of these issues are not deeply looked at in altimetry. However, I find some specific sections lacking in grammar and scientific explanations.

“ We thank the reviewer for constructive and suggestions (shown in italics). Our responses are given below. As suggested, we have reviewed carefully the entire manuscript and removed redundancies, we have corrected grammatical issues and have improved the clarity of the figures as shown in the revised manuscript. General comments:

(1.) The font needs to be increased on all figures, currently they are too small and the text is difficult to make out. Please, also put the units of each figure inside brackets, such as “/dB” to “(dB)”. Add more text to the captions that provide more explanation of what they describe, or what to look for; what should the reader look at? This helps the reader, as they do not need to go back into the manuscript looking for the associated information. I personally don't like the use of yellow in the figures, as it is hard to see sometimes, but that I will leave up to you.

“ We have changed the color scale in each figure and provide more information in the captions.

(2.) The latter part of the introduction needs to be reorganized, as it jumps between altimetry missions and snowpack properties.

“ As suggested by the reviewer in the technical comments, we have reorganized the introduction to correct for this problem.

(3.) I would also like the boundary of the two zones to be drawn on each map to easily

C2

identify them.

ââumlaccedil As suggested by both reviewers, the boundaries of the SP zone have been drawn on each map. These boundaries show regions where the backscattering coefficient at the Ku band peaks before April. We have also changed the color scale and have plotted a cross mark on the map to indicate the location of data point shown in figure 1.

(4.) Further, you say that a major limitation of the work is the lack of knowledge of the surface roughness. Have, you explored the use of ICESat for this (good overlap with Envisat)?

ââumlaccedil We did not closely look at the ICESat data. The radar backscatter is related to the surface roughness at the scale of the radar wavelength (Ulaby et al., 1982) and larger. Here, radar wavelength are less than tens of centimeters (0.8 cm, 2.3 cm and 9.4 cm for Ka, Ku and S bands, respectively) while ICESat provides only surface elevation profiles at the metric-to-kilometric scales. This prevents us to use such surface roughness.

(5.) I think the last paragraph in the conclusion (L.310-L.316) should be re-written to more clearly state your conclusions, as I don't agree with the statement that "This as "this study mitigates". This implies that you have somehow "physically" reduce the error or corrected for it. I think its fairer to say that you have pointed to important factors that has to be considered when choosing or selecting frequency bands for new missions. Further, I would like (ii) and (iii) to be slightly more informative; how should (ii) be interpreted and why does (iii) undergo large changes etc.

ââumlaccedil As suggested by the reviewer, we have rewritten the last paragraph of the conclusion. The (ii) and (iii) have been removed and we have specified what have been done. Now reads (Line 327) :

"This investigation provides new information on the Antarctic Ice Sheet surface seasonal dynamics and provides new clues to build robust correction of the altimetric

C3

surface elevation signal. Multi-frequency sensors are the key to improving the understanding of the physics of radar altimeter measurements over the AIS. An important limitation of this study is the lack of information on the seasonal variability of the snow surface roughness in Antarctica, which will be the topic of future work."

Detailed comments:

L.8 "altimeter" to "altimeters"

ââumlaccedil The correction has been made.

L.9 "snowpack" to "snowpack,"

ââumlaccedil The correction has been made.

L.15 "S, Ku and Ka bands" to "different frequencies"

ââumlaccedil The correction has been made

L.16 "Ka-band" to "Ka frequency"

ââumlaccedil The correction has been made.

L.17 "In contrast, the cycle is dominated by the surface echo at the S band" to "In contrast, at the S band, the cycle is dominated by the surface echo"

ââumlaccedil The correction has been made. The sentence now reads (Line 19):

"In contrast, at S band, the cycle is dominated by the surface echo."

L.18 "At Ku band, which intermediate in terms of wavelength between S and Ka bands, the seasonal cycle is in the first zone dominated by the volume echo and by the surface echo in the second one" This sentence is confusing what is the first and second zone? Also, you can remove the points that Ku is between S and Ka-band as it is redundant.

ââumlaccedil We have corrected for this confusion and added more information on the zones. The sentence now reads (Line 13):

C4

“We identified that the backscattering coefficient at Ku band reaches a maximum in winter in part of the continent (Region 1) and in the summer in the remaining (Region 2) while the evolution at other frequencies is relatively uniform over the whole continent.”

“At Ku band, the seasonal cycle is in the Region 1 dominated by the volume echo and by the surface echo in the other one.”

L.20 You say that seasonal and spatial variations should be accounted for, but how should this be done?

â€” The corrections suggested by the reviewer on L15 to L20 have been made and the text reworded as follow:

“We identified that the backscattering coefficient at Ku band reaches a maximum in winter in part of the continent (Region 1) and in the summer in the remaining (Region 2) while the evolution at other frequencies is relatively uniform over the whole continent. To explain this contrasted behavior between frequencies and between regions, we studied the sensitivity of the backscattering coefficient at three frequencies to several parameters (surface snow density, snow temperature and snow grain size) using an electromagnetic model. The results show that the seasonal cycle of the backscattering coefficient at Ka frequency, is dominated by the volume echo and is mainly driven by snow temperature evolution everywhere. In contrast, at S band, the cycle is dominated by the surface echo. At Ku band, the seasonal cycle is in the Region 1 dominated by the volume echo and by the surface echo in the other one. This investigation provides new information on the seasonal dynamics of the Antarctic Ice Sheet surface and provides new clues to build more accurate correction of the radar altimetric surface elevation signal in the future.”

L.23 Remove “within”

â€” The correction has been done.

L.23 “of polar” to “of the polar”

C5

â€” The correction has been done.

L.24 “changes in volume” to “the volume change”

â€” The correction has been done.

L.29 “distance observed” to “observed distance”

â€” The correction has been done

L.30 “leading” to “, leading”

â€” The correction has been done.

L.33 “called” to “called the”

â€” The correction has been done.

L.35 “correct” to “corrects for”

â€” The correction has been done.

L.36 Change to: “To reduce the effect of the spatially varying radar penetration bias”. .

â€” The correction has been done.

L.37 “use” to “used”

â€” The correction has been done.

L.37 Zwally et al (2005) used elevation residuals (crossover differences) not elevation.

â€” The correction has been done.

L.38 As far as I know Flament et al (2012) used a linear model, solved with OLS, to estimate the sensitivity gradients. Where does the non-linear relationship come from?

â€” Yes, we agree Flament et al. (2012) have really used a linear model not non-linear

C6

as we have written. We have corrected this.

L.39 “the whole” to “all”

âĀĀ The correction has been done.

L.42 “of” to “in the”

âĀĀ The correction has been done.

L.44 “of” to “of the”

âĀĀ The correction has been done.

L.44 “penetrating” to “interacting with”

âĀĀ The correction has been done.

L.45 What information on the snow pack properties does it provide?

âĀĀ The following snowpack properties have been cited in bracket on Line 52 :

“(surface roughness and density, temperature, grain size, and stratification)”.

L.50 “The ENv. . .” This entire section and the SARAL/Altika section should be moved down

âĀĀ We have moved the paragraph to a more appropriate place in the introduction on Line 65.

L.60 “The radar wave. . .” This section should be moved to L.49

âĀĀ We have moved the paragraph to a more appropriate place in the Introduction on Line 58.

L.66 “This study is structured. . .” Remove this section it’s redundant the reader can already understand it from the headlines.

âĀĀ As suggested by the reviewer we have removed the corresponding text.

C7

L.80 “vertical sampling resolution” to “range gate resolution”

âĀĀ The correction has been done .

L.82 “25 of February” to “25th of February”

âĀĀ The correction has been done.

L.85 same as L.80

âĀĀ The correction has been done.

L.86 remove “thus”

âĀĀ The correction has been done.

L.87 Rewrite sentence “The frequency ...” by remove ratios

âĀĀ The sentence has been reworded as follow on line 89 :

“ The difference between the Ka and Ku bands, and the Ka and S band are up to a factor of 2.7 and 11.6, respectively, which results in different sensitivity to the surface and the subsurface characteristics.”

L.95 “cycles of” to “cycles of Envisats”

âĀĀ The correction has been done.

L.97 “cycle sigma of” to “cycle of sigma”

âĀĀ The correction has been done.

L.98 “fitting the time series of the observations with the following function” to “fitting the observations with the following model”

âĀĀ The correction has been done.

L.103 “i is the index of the along track data” Comment: This needs to be explained more thoroughly! How large are the bins (search radius). Can you also further elaborate on

C8

how you get the number of equations in more detail.

â€” The text was incomplete. The previous corrections and suggestions from the first reviewer will make this sentence more clearer and informative. The sentence now reads on line 105:

“... i represents the data point over the continent.”

L.104 “leading to robust inversion” Comment: How is this a robust inversion? Do you edit the data (3-sigma)? I think you mean as you only have three parameters to fit? If so just remove robust and say you solve with OLS. Further, how was the gridding performed you need to elaborate on that.

â€” As suggested by the reviewer we have corrected and added a text to explain thoroughly how the data are gridded. It is worth noting that the results were interpolated on a map of 5km*5km grid only for visualization needs. The sentence now reads on line 105:

“ The fit was done with the Ordinary Least Squares (OLS) method and all data points with time-series length less than 11 cycles (about a year) were discarded. The date at which σ_0 reaches a maximum within a seasonal cycle is obtained by converting the seasonal phase to fraction of a year (assuming a year counts for 360 days). We have found that along track analysis of the seasonal parameters of σ_0 showed no dependence to anisotropic effects. In the following, both ascending and descending measurements are mixed to keep a high density of observations and cover most AIS (1.9 million data points). For visualization needs, seasonal parameters are interpolated on a map of grid by averaging with Gaussian weights. We considered all data points within a 25 km radius and weighted with a decorrelation radius of 10 km.”

L.108 “on snow” to “of snow”

â€” The correction has been done.

L.110 “echo and” remove echo

C9

â€” The correction has been done.

L.111 “been previously. . .” to “been previously studied by Lacroix et al (2008)”

â€” The correction has been done.

L.112 Remove everything after Remy et al. (2015)

â€” The sentence has been modified as suggested. The sentence now reads on line 118 :

“The physics involved in both surface and volume echoes have been previously studied by Lacroix et al., (2008b).”

L.114 Rewrite first sentence to something “The snow surface can be modeled as. . .”

â€” The text has been rewritten. The sentence now reads on line 121:

“The snow surface can be modeled as a randomly rough surfaces because most naturally occurring surfaces are irregular.”

L.115 “from rough” to “from a rough”

â€” The correction has been done.

L.116 Change to “The effective dielectric constant of the snow is”

â€” The correction has been done.

L.117 “of snow” to “of the snow” and “and ice” to “and the ice” and “prescribed” to “modelled”. Remove “statistical geometries”

â€” The correction has been done. The sentence now reads on line 123 :

“The effective dielectric constant of the snow is a function of snow the density and the ice dielectric constant, while the roughness is usually modeled by two parameters: the surface correlation length (l) and the standard deviation of the surface elevation (l) (Ulaby et al., 1982).”

C10

L.118 "height" Comment: Use either height or elevation

âĀĀ We have changed "height to elevation" along the manuscript.

L.119 put "compared to the radar wavelength" into brackets, and add ";" after "coefficients" and add "a" after "from".

âĀĀ The correction has been done.

L.120 remove "the roughness has" and "as follows"

âĀĀ The correction has been done. The sentence now reads on line 125:

" In the case of large standard deviations of the surface elevation (σ) (compared to the radar wavelength), the backscattering coefficient, from a rough surface can be estimated assuming a Gaussian auto-correlation function (Ulaby et al., 1982):"

L.122 "at normal" to "at the normal" and add "angle" after "incident"

âĀĀ The correction has been done.

L.125 Remove entire sentence "When the surface snow. . ." it's redundant.

âĀĀ As suggested by the reviewer, the redundant sentence has been removed.

L.149 Remove "all"

âĀĀ The correction has been done.

L.150 Remove "first"

âĀĀ The correction has been done.

L.168 "appears in yellow" Comment: I think you should draw the boundary of the area in your figures to allow the reader to easier detect them.

âĀĀ As suggested by the reviewer, we have revised all the figures and added the SP zones boundaries in the figures.

C11

L.175 When using Julian days please also provide the months inside brackets

âĀĀ The correction has been done.

L.195 please change "dhds" to "dh/ds" (s=sigma)

âĀĀ The correction has been done.

L.203 Remove "the" before "snow" and put "it is poorly known" inside brackets

âĀĀ The correction has been done.

L.211 "on volume" to "on the volume"

âĀĀ The correction has been done.

L.212 "bands" to "band levels."

âĀĀ The correction has been done.

L.217 "volume" to "medium"

âĀĀ The correction has been done.

L.217 "Along increasing" Comment: Long sentence, should be re-written.

âĀĀ The sentence has been rewritten. The sentence now reads on line 230:

"Also increasing snow grain size increases the scattering coefficient, which in turn increases the radar extinction in the medium. It results in a decrease of the radar wave penetration, therefore may limit the volume echo."

L.218 "which increases" to "which in turn increases"

âĀĀ The correction has been done.

L.222 "temperature wave" maybe to "temperature gradient" and replace "to the subsurface of the" with "into". Further change "The volume echo variation" to "The variation in the volume echo"

C12

â€” The correction has been done. The sentence now reads on line 233:

“This lag is related to the propagation of the temperature gradient from the surface into the snowpack. As the temperature controls the snow grain metamorphism and the radar wave penetration depth, the variation in the volume echo would be predominantly driven by the seasonal variations of snow temperature.”

L.224 “echo increases” Comment: Increases in what; magnitude? Make clearer!

â€” The correction has been done. The sentence now reads on line 236:

“The magnitude of these echoes increase with increasing surface snow density, thus similar seasonal cycle of σ_0 would be expected at any frequency if snow density were the main driver.”

L.239 remove “that of”

â€” The correction has been done.

L.244 “the increase” Comment: See L.224

â€” The correction has been done.

L.247 “which one among . . .” Sentence is worded strangely; please re-write

â€” As suggested , the sentence has been rewritten. The sentence now reads on line 262:

“However, in this study it is difficult to differentiate with certainty between the surface snow density and the snow surface roughness, that drives the seasonal cycle of the surface echo.”

L.256 Remove “which” after matches, replace “greatest” with “large” and replace “of” before “radarsat” with “from”.

â€” The correction has been done.

C13

L.269 “the distribution” to “the spatial distribution”

â€” The correction has been done.

L.277 “in blowed” sounds strange please change sentence structure or remove.

â€” The correction has been done.

L.283 add months after Julian days and change “By blowing” into “Persistent winds” or similar

â€” The correction has been done. The sentence now reads on line 301:

“Cold and persistent winds may unusually accelerate the cooling of the surface snow temperature (Remy and Minster, 1991).”

L.288 “highest grain size vertical gradient” to “the highest vertical gradient in grain size”

â€” The correction has been done.

L.290 “difference observed” to “observed difference”

â€” The correction has been done.

L.294 This sentence sounds strange, maybe start something like this: “This study, using 35-day repeat radar altimetry data, allowed for. . .”

â€” The correction has been done. The sentence now reads on line 312:

“This study, using 35-day repeat radar altimetry data, allowed for carrying out this spatial and temporal comparative analysis of the seasonal amplitude and date of maximum σ_0 at the S, Ku and Ka bands.”

L.295 “used 8-year” to “used an 8-year”

â€” The correction has been done.

L.296 “band,” to “band a” and “and 3-year” to “and a 3-year”

C14

â€” The correction has been done.

L.297 “band all” to “band” and “covering 2002” to “covering the time period of”

â€” The correction has been done.

L.300 remove “on the AIS”, add “with a” before “maximum” and “the” before “winter”

â€” The correction has been done.

L.302 Remove “the” before “snow” and add “the seasonal changes in the” before “volume echo”

â€” The correction has been done.

L.303 Remove “the” before “snow properties”

â€” The correction has been done.

L.304 replace “because” with “due to” and “those properties” with “those parameters”

â€” The correction has been done.

L.306 Remove “which is between the S and Ka bands”

â€” The correction has been done.

L.307 “zones is” to “zones are”

â€” The correction has been done.

L.308 “or not” to “lack of”

â€” The correction has been done.

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