Review of: Radio-echo sounding measurements and ice-core synchronization at Dome C, Antarctica

Anna Winter et al. 2016, *The Cryosphere.*
Reviewer: Tom Jordan, University of Bristol, 11th July 2016.

Summary

The manuscript provides a detailed compatibility study of RES data from five different radar systems in the Dome C region, and is focused around the detection of Internal Reflection Horizons (IRHs). Their primary glaciological motivation, which is well emphasised throughout, regards synchronisation with ice core data and Oldest Ice characterisation. They present comparative A-scope and Z-scope plots, and are able to relate the different features present to the differing radar system characteristics. As part of the study they use an electromagnetic modelling framework and the dielectric profile of the ice core to estimate a `synthetic' radar trace. The synthetic trace is a valuable component of the investigation as it enables them to establish a causal link between the dielectric properties of the ice layers and the internal reflections present in the radar traces. Detailed discussion of relevant uncertainty and spatial variability is provided. The authors conclude that the AWI, UTIG and CReSIS systems provide the best resolved internal layers, and have the best potential to be combinable. Additionally, the synthetic trace/age conversion enables the authors to conclude ~10 IRHs can be well synchronised with the ice core timescale.

General comments

Overall the scientific analysis is of a high quality and the manuscript is well written. I have, however, made a few suggestions where more detail and precision in the presentation is required; particularly in the methods section. The manuscript is well structured and referenced, with informative figures and tables. Regarding the novelty of the study, I think it needs to be made more explicit as to what differentiates the manuscript from Cavitte et al. 2016 (which also considers IRH detection at Dome C for different radar systems). I appreciate that there are differences, (e.g. the use of the synthetic trace in this study), but this may not be obvious to the general reader.

The electromagnetic modelling framework for the synthetic trace appears well established, and physically rigorous. However, given the overall emphasis on comparing how radar system characteristics influence the sounding data, one major area which requires explicit investigation is frequency dependence (see specific comments, Sect. 2.2, Sect. 5.1). Whilst probably not directly impactful for Oldest Ice/synchronization, frequency dependence could be important for combining IRH data sets where reflection amplitudes are important, and thus is required to complete the overall compatibility aspect of this study.

The manuscript is clearly of general interest to the readership of *The Cryosphere*. RES of IRHs can provide useful glaciological information that goes substantially beyond ice core chronologies; for example temperature (from attenuation) and ice dynamics (from IRH derived metrics such as the continuity index). Such a comprehensive compatibility study between different radar systems is therefore of suitably high impact, and will no doubt be a central reference point for future studies which combine RES data sets. Whilst I appreciate that the glaciological application here is Oldest Ice, I have made a few specific comments regarding how the authors could broaden the scope of their introduction and discussion.

Specific comments

1.

A clear case needs to be made in the introduction what differentiates the study (both in terms of the questions addressed and the methods that are used) from Cavitte et al. 2016.

As mentioned in the general comments, I think the emphasis in the introduction on Oldest Ice is too narrow. This is an excellent opportunity to communicate to the wider glaciological community what rich information is present within RES data (in particular derivable from IRHs), and therefore could be exploited on a broad scale if different data sets can be combined. Two relevant examples are: depth-averaged temperature (from the attenuation rate inferred from internal reflections), Matsuoka et al. 2010, Macgregor et al. 2015b, ice dynamics (from the IRH continuity index) Karlsson et al. 2012.

2.1

It would be helpful here to provide more information regarding the DEP method and the gamma absorption method. In particular; how some of the underlying assumptions/restrictions of these methods could impact the rest of the investigation. For example, in the case of the DEP method, I think that it is important to note explicitly that the reference frequency (100 kHz) is significantly less than the radar systems (~100 MHz), which may be important regarding frequency dependence of dielectric conductivity/attenuation (see recent discussion in Macgregor et al. 2015b)

2.2

Given the range of radar system frequencies that are considered in this study (60-195 MHz) I think it is necessary to investigate the frequency dependence of the synthetic trace. Note; that this is in the context of thin-film interference (and how frequency/wavelength dependence affects the peaks/relative amplitudes of the synthetic trace) rather than the intrinsic frequency dependence of the dielectric conductivity as mentioned above. Specifically, it would be useful to repeat the synthetic trace analysis, for source wavelets at the CReSIS (195 MHz) and UTIG (60 MHz) centre frequencies. If pronounced sensitivity is demonstrated, then these repeat traces could be used to improve the comparison between the synthetic A-scope trace and the radar A-scope traces in Section 5 and the related discussion in Section 6. I hope, given the excellent EM simulation framework available to the authors, this is request is fairly straightforward to do, and would add a significant value to their investigation.

On a related note, I assume that the EM simulations assume a monochromatic source? Since the chirped radar systems have both finite and differing bandwidths, this is clearly an important simplification. Finally, is it also correct that the EM simulation method is physically a closer representation of the pulse/burst systems rather than the chirped radar systems? Again this needs to be discussed, along with potential caveats for cross-comparison.

2.3

Given the overall emphasis on cross-comparison between different radar systems, it is desirable that the authors provide evidence for how robust the method used to determine the permittivity of ice is for other radar systems (only AWI is discussed here). The variance in the obtained values could then be discussed in relation to other components of their investigation.

5.1

If possible I would like to see a discussion (and potentially an explanation) for the variation in the relative amplitude of the IRH peaks for the different radar systems. In particular, the relative amplitude of the peaks for the UTIG trace appears to be lower than the other systems of comparable vertical resolution (AWI,CReSIS), and this may potentially relate to frequency dependence. One reason why reflection amplitudes are important is that they are used to determine depth-averaged attention rates (and thus information about depth-averaged temperature). Subsequently, even if only preliminary conclusions be made regarding differences in amplitude, this will be useful for future combination studies.

Since it is mentioned in the conclusions that AWI, CReSIS and UTIG are likely suitable for combined analysis, it would be useful to see some direct cross-over analysis of the traces. I appreciate from Fig 1 that this may only be possible for AWI and UTIG, but this would act to strengthen the overall conclusions regarding combining data.

6.1.1

I think it would be helpful here (or potentially in the caption of table 1) to provide relevant equations regarding the relationship between bandwidth and vertical resolution for the chirped systems (e.g. as supplied in the CReSIS reference).

6.2.1

Is it possible to provide a rough estimate of the radar footprint diameter in the Dome C region? My guess is that as we are dealing with comparatively thick ice this would be toward the upper end (or possibly exceed) the range that is stated.

7.

As with the introduction, I think a clear case needs to be made what distinguishes the conclusions of this study from Cavitte et al*.* 2016.

I think it also needs to be discussed explicitly in the conclusion how variable vertical resolution (particularly how multiple peaks transition to single peaks as function of vertical resolution), pose challenges for combining data sets. This discussion will hopefully also address other glaciological information derivable from IRHs.

Minor comments, typographical errors, etc.

Note; I use the symbol `→**'** to indicate my suggestions for ` replace with'.

General

There are quite a few examples where there is no white space preceding the SI units. (e.g. 0.2m). These should be corrected.

Be consistent with the hyphenation of ice-core/ice core

There are many instances where use of `vertical resolution' would be less ambiguous than `resolution'.

1.

Line 17: It would be helpful to add a reference here.

For brevity, the final paragraph of the introduction could be dropped.

2.1

Line 1: ice: → ice (: should only be used for equation arrays/lists)

Line 9: Reword `we shortly discuss the input parameter permittivity of ice.

Lines 11-13: If possible, please reference the core data (temperature, accumulation, etc.)

Lines 18,22: Give units for sigma and rho when they are introduced.

Lines 24,27: Unit spacing for Xmm

Line 24: measuring: → measurement

Line 25: comma before rho_ice

2.2

Title: Consider changing to `Electromagnetic modeling of radar traces'

Line 1: ice: → ice (: should only be used for equation arrays/lists)

Line 4/equation 2: The equation is correct, but the symbols (epsilon,epsilon',epsilon'',sigma, omega) must be introduced correctly in text; see, for example, Eisen, et al. 2004, equation (1). Additionally, episilon_0 is best described as the `vacuum permittivity' (the use of ordinary is confusing since `ordinary permittivity' is used in the context of anisotropic media).

Line 14: `incorrect ordinary permittivities (the real part of the complex relative permittivity)' → `incorrect real permittivities'.

Line 24: Measuring → measurement

Line 17. '1D-FD' → '1D-FD (One-Dimensional Finite Difference).'

Line 19: Please be more specific about the boundary condition(s). Is it the lower or the side boundaries?

Line 20. Please reference the Courant Criterion, and state what it tests for (convergence of the numerical solution).

Line 21. See my specific comment about the frequency dependence/sensitivity of the synthetic trace. It should be clearly started here that there are differing frequencies and bandwidths for the radar systems.

Line 24. Please provide a reference for Hilbert magnitude transform.

2.3

Title: Consider changing to `Determination of the relative permittivity of ice'

3.2

Line 17,22: Unit spacing for X microseconds.

3.4

Line 27: Unit spacing for km.

3.5

Line 27: Unit spacing for MHz.

For completeness it would be helpful to list the distances of the profiles from Dome C for all radar systems (this is only provided for AWI and CReSIS).

4

Line 15: No new paragraph?

5.1

Line 12: second → upper right

Line 18: resolution → vertical resolution

5.2

Line 6: y → vertical

Line 8: about → an approximately

Line 17: is starting → starts?

Line 32: missing → missing from the synthetic trace

5.3

Line 2: Is there a suitable reference for the `sensitivity approach' used here?

Line 15: The advantage → The advantage of the sensitivity approach…?

6.1.1.

Title: Consider changing to `Vertical and horizontal resolution'

Line 14: UTIG systems the→ UTIG systems to be the?

Line 15: Obviously in → Due to their lower vertical resolution

Line 25: continue → continue with

6.1.2

Line 3: remove `and others'

Line 8: accumulated → accumulates?

Line 10: it is → the slope is

Line 13: Urbini et al. needs a date.

Line 14/15: Reword sentence starting: `That would…

Line 22: they → this

6.1.3

Line 8: comparing → comparative

6.2

Lines 12-14: 6.2.2. and 6.2.1 are introduced in the wrong order.

6.2.1

Lines 19,20,28: Unit spacing for Xm

Line 23: examine → who examine

Line 28: find → found

6.2.2

Line 14: missing full stop after trace

Line 15: remove `used'?

Line 27: example: The → example, the

7.

Line 9/10: It probably best to relate the well resolved IHRs for these systems directly to their better vertical resolution than the other systems (rather than implicitly through their bandwidth).

Line 13: Reword: The best quality in imaging the basal layer have the CReSIS,
UTIG and BAS data, the latter, however, with …

Line 14: Reword

Line 19: Remove `profound' (it is best practice to avoid superlatives)

For the conclusions it is best practice to use past tense rather than present tense, and I would recommend carefully checking this section.

Tables, figures and captions

The tables and figures are both informative and well presented. I do, however, have a few suggestions.

Table 1

Relabel `resolution' as `vertical resolution'. For completeness it would be desirable to provide an indication of how windowing/processing affects the vertical resolution (e.g. for the CReSIS system I believe that the post-windowed vertical resolution is ~4.3 m).

Fig 2.

Given that the reflections are ultimately caused by discontinuities in conductivity (rather than the peaks themselves), I think it would be useful to provide a plot of the vertical gradient of conductivity underneath the conductivity plot. I wouldn't be surprised if this gradient plot has a more `immediate' correspondence with the synthetic trace reflections, and could be used to improve the analysis in Section 5 and 6.

Following the terminology in Section 4, it should be added explicitly to the caption that Fig. 2 is an A-scope plot

Fig 3.

The font size for the axes labels/numbers should be increased

of → for

x-axis → horizontal axis

closer →closely?

References

Cavitte, M. G., Blankenship, D. D., Young, D. A., Schroeder, D. M., Parrenin, F., Lemeur, E., Macgregor, J. A., and Siegert, M. J.: Deep radiostratigraphy of the East Antarctic plateau: connecting the Dome C and Vostok ice core sites, Journal of Glaciology, 2016.

Eisen, O., Nixdorf, U., Wilhelms, F., and Miller, H.: Age estimates of isochronous reflection horizons by combining ice core, survey, and synthetic radar data, Journal of Geophysical Research: Solid Earth (1978–2012), 109, doi:10.1029/2003JB002858, 2004.

Karlsson, N. B., Rippin, D. M., Bingham, R. G., and Vaughan, D. G.: A ‘continuity-index’ for assessing ice-sheet dynamics from radarsounded internal layers, Earth and Planetary Science Letters, 335, 88–94, doi:10.1016/j.epsl.2012.04.034, 2012.

Macgregor, J. A., Li, J., Paden, J. D., Catania, G. A., and Clow, G. D.: Radar attenuation and temperature within the Greenland Ice Sheet, Journal of Geophysical Research: Earth Surface, 120, 983–1008, doi:10.1002/2014JF003418, 2015b.7/jog.2016.11, 2015b.

Matsuoka, K., Morse, D., and Raymond, C. F.: Estimating englacial radar attenuation using depth profilesof the returned power, central West Antarctica, Journal of Geophysical Research, 115, 1–15, doi:10.1029/2009JF001496, 2010.