Reply to Interactive comment on “Radar stratigraphy connecting Lake Vostok and Dome C, East Antarctica, constrains the EPICA/DMC ice core time scale” by M. G. P. Cavitte et al.

<u>Anonymous Referee #1</u>

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Cavitte et al. tracked isochronous englacial radar reflectors between EPICA Dome C and Vostok ice cores, in order to better constrain the depth-age relationship of the Dome C ice core. In general, this manuscript is not well organized so hard to follow.
The structure has now changed.

The title says that radar constraints of ice-core time scales are reported, but the abstract says no specific results how this method improved the ice-core time scales.
Title has been changed to reflect the new focus.

In section 2 (data and methods), it is said that the propagation speed is assumed to be 169 m/usec citing Carter et al. but without any further justifications of this assumption. Nothing is said that this propagation speed is further examined later. Suddenly, uncertainty of this assumption is discussed very end of Section 3.1.
We now have a whole section dedicated to error analysis (section 3.2) with a supplementary depth-error estimation discussion in Supplement 1.
The propagation speed has been changed to 168.5 m/usec, which corresponds to a dielectric constant of 3.17. Peters et al. (2005) use 3.17 as the reference value for glacial ice in their analysis of coherent radar sounding techniques using our radar system. Variations in the value of the dielectric constant are then assessed and integrated in our radar layer depth errors.

[Major points]

1. The weakest point of this paper is that a uniform radio-wave propagation speed of 169 m/usec is assumed. The propagation speed is a function of density (i.e. firn thickness), ice temperature, and ice fabrics. This study accounts for the firn effects; the other two affect less but significant. The deepest tracked radar reflector is 2300 m deep at Dome C ice core site, which corresponds to the two-way travel time of 27.2 usec if the speed is 169 m/usec. The speed in "pure" ice can vary between 168 and 169.5 m/usec (Fujita et al., 2000, Physics of Ice Core Records). This speed range gives the depth uncertainty of 21 m. According to Figure 5, this depth uncertainty gives the age uncertainty of 3-5 ka. It is possible to accurately estimate the depth profiles of the propagation speed, in terms of firn density (this is done using Equation 1), ice temperature, and fabrics, using the ice-core data. Propagation speed dependences on these factors are not unique but it is reasonable to assume that the same dependences can be applied to these two ice cores. This assumption is valid if the same physical mechanisms control the dielectric processes in these ice cores. Such analysis is necessary to define the uncertainties of this radar-based chronology.

We have now taken into account wave propagation speed variations in our radar layer depth errors.

We use a reference value of 168.5 m/usec as the speed of EM waves in ice, using a reference dielectric constant of 3.17 (see reply to comment above). We then consider the full range of possible dielectric constant variations at the two core sites (3.13 – 3.19) and compute the wave propagation velocity error associated with these variations.

Temperature, crystal fabric and impurity content variations are all three evaluated. To provide conservative error measurements, we used the maximum possible variations for each of these variables.

In more detail:

-Temperature: we used temperature curves published for each ice core to estimate the temperature difference between our shallowest and deepest radar layers and used Dowdeswell and Evans (2004)'s relationship between temperature and dielectric constant values to compute the maximum variation in the latter. We

obtained a wave velocity in ice (C_{ice}) of 168.5±0.32 m/usec and 168.5±0.35 m/us at Dome C and Vostok respectively.
-Crystal fabric: we used Dowdeswell and Evans (2004)'s quoted dielectric constant variation for the maximum anisotropy effect. We obtained C_{ice} = 168.5±0.47 m/usec.
-Impurity content: we used Dowdeswell and Evans (2004)'s quoted dielectric constant variation for impurity concentration variations as might be found in temperate glaciers, which would be much smaller for polar ice. We obtained C_{ice} = 168.5±0.20 m/usec.
These wave velocity variations were then combined as a root-mean square (rms) C_{ice} error value. These were then translated into a depth error for each radar layer using the range precision errors calculated for each radar layer.
Firn depth errors were also folded into our radar layer depth errors.
Table 1 lists the final radar layer depth errors. An error analysis section has now been added (Section 3.2).

2. The radar instruments used for this study have 100-250 nsec pulse widths, which correspond to the vertical resolutions of 8-21 m. In other words, a single radar reflector is made up with interference of the radio waves reflected from individual interfaces of the dielectric conductivity over this depth range. The depth of a radar reflector at the core site does not necessarily give the accurate depth of the reflection origin. Practically speaking, it is necessary to examine depth profiles of DEP (or similar dielectric conductivity) records in order to find the dominant source of each radar reflector. If there are multiple DEP peaks with similar magnitudes, it is impossible to identify the single source of the reflection origin, so the chronology uncertainty should be equivalent to the radar resolution, 8-21 m. The authors present these resolution ranges in Section 3.1 but do not estimate uncertainty in depth and corresponding age, associated with the resolution, digitizing, and reflector-pick uncertainties. More importantly, dielectric profiles and radar reflector depths are not examined together. Resolving these two issues is necessary, before Sections 3 and 4 are fully evaluated.

Before we discuss this point, we want to report that our radar pulse widths have been revised to the pulse widths measured directly from the radar layer returns on the transects intersecting the ice cores. We believe this is a more accurate measure of the pulse widths, which takes into account pulse compression and filtering processes that modify the theoretical radar pulse width.

In this study, our aim is to obtain a precise measure of depth for the radar layers connecting the two core sites. We are not attempting to differentiate closely spaced radar layers, which would then be limited by the radar full range resolution, but rather, we aim to precisely locate the depths of a set of strongly specular layers (layers chosen based on this criteria by the interpreter). Our precision in locating these layer depths is a function of the range resolution but also of the signal to noise ratio for each radar layer depth considered. The signal to noise ratio of each layer return ultimately determines how precisely we can identify the peak energy of a radar return, i.e., our radar layers. We call this depth error "layer range precision error σ_{r^*}".

Supplement 1 gives a detailed discussion of this error rooted in the astronomy literature and gives the maximum and minimum layer range precision error values obtained in this study.

We examined the DEP and ECM profiles published for each core at Dome C and Vostok respectively (no two DEP or ECM profiles have been made publicly available to date for both cores for the depths considered here). We plotted these for our radar layers belonging to the penultimate glacial cycle, since the corrupted layers that are associated with the last glacial period would give corrupted depths. Both the ECM and the DEP data had to be smoothed with a low pass filter before any analysis could be done due to the high density of ECM and DEP peaks.

The deepest Vostok ECM profile has only been measured down to 2000 m to date (Parrenin et al., 2011) and therefore restricts our ECM - radar data comparison to our 7th and 8th layer depths (radar layers wlk03a and wsb3).

Figure 1 and 2 are plots of the radar layer depths overlain on the ECM and DEP profiles for Vostok and Dome C respectively, for which we show the radar layer depth error as grey lines. In general any number of peaks align with our interpreted RES layers implying that the largest unknown is likely the unknown ice core depth errors. Parrenin et al., (2012) quote:

> "A drawback of the logging depth is its off-set to the true depth, which is used in glaciological models. [...] Offsets [...] can sum up to several meters for a deep drilling and could mostly be corrected for, but to our knowledge it has never been applied."

ECM/ DEP comparisons with respect to radar layer stratigraphy will ultimately require unequivocal knowledge of the absolute depth errors between the two.

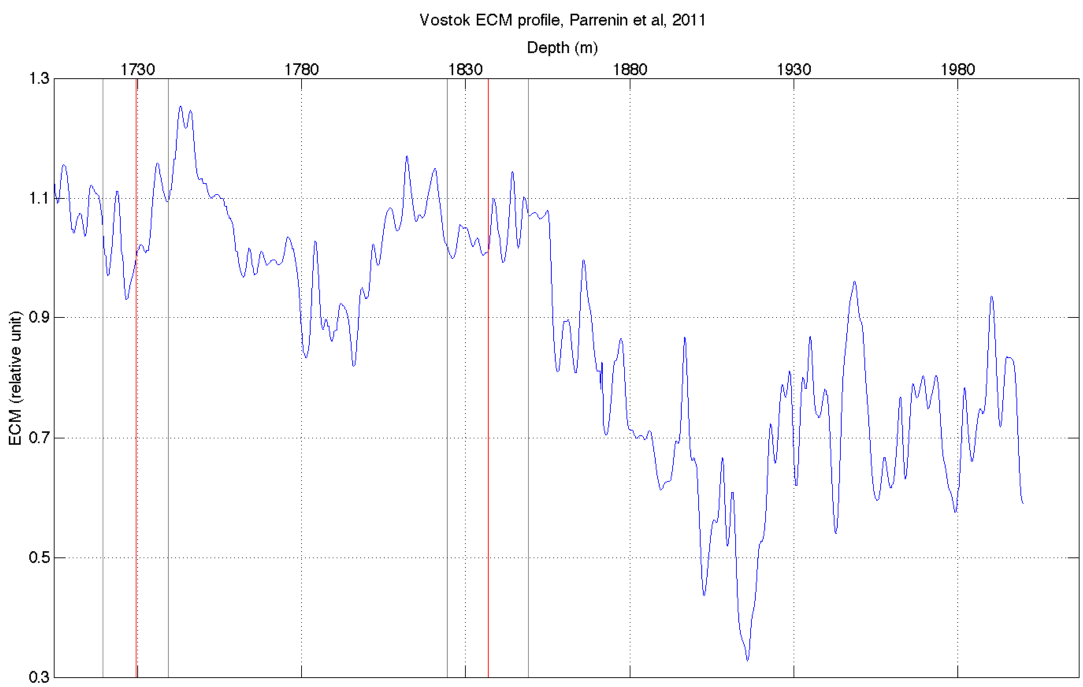

Figure 1. Plot of ECM profile at the Vostok ice core (Parrenin et al., 2011) with radar layers overlain in red. Radar layer depth errors are plotted as gray bounding lines.

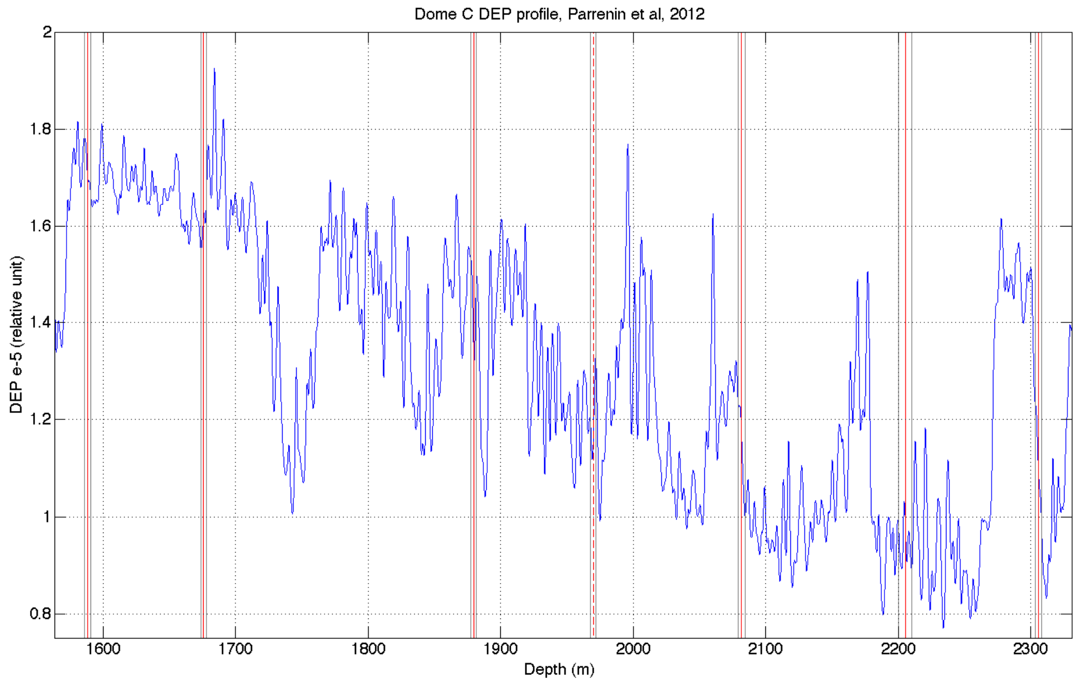

Figure 2. Plot of DEP profile at EPICA Dome C ice core with radar layers overlain in red. Radar layer depth errors are plotted as gray bounding lines.

[Editorial issues]

- "Horizon" is used frequently, to refer radar reflector(s). However, a reflector is not a horizon. Also "layer" is used many times casually. A layer refers a unit of the ice that has a certain thickness. I think that "reflector" is a better word to describe what was observed in the radar data. The use of "layering" is acceptable, but please consider using "reflector stratigraphy" instead.

We agree that the term "horizon" might be ambiguous. We therefore choose to use "radar layer" or "layer" simply to convey that concept of ice thickness packet.

- Page 322 line 21. The reference should be Suwa and Bender, not Bender and Suwa.

Changed.

- Page 322 line 24. Kawamura (2009) is a newsletter article, not peer-reviewed. Please make every effort to cite peer-reviewed paper.

Removed.

- Figure 1: what is the yellow line between C and C'?

This refers to the dashed line on the basemap (Fig. 1). We have now changed the color to red for better of visualization and included this symbol in our basemap legend.

- Figure 2: It is quite hard to understand. Please rewrite the caption.

Done.

- Figures 3 and 4: it is critical for this manuscript to show how these radar reflectors are tracked. Current figures show the radar images and picked reflectors together so it is hard to see how these picks are valid. Please show two radar image and picked reflectors in separate panels placed next to each other.

Done.

- Figure 5: I cannot see any justification to use a simple cubic-spline interpolation to tie spontaneous radar-constrained depth-age points.

We have now used the simplest piecewise linear interpolation between radar depth-age points.