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 #2</u>

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General comments

Cavitte and others extracted 11 tie points between the Vostok deep ice core and the EPICA Dome C (EDC) ice core by tracking Z scope image data of the radar sounding. The pulse widths of the radar were 250 n-second (~21 m in EM wave in ice) or 100 n-second (~8m in ice). By assuming errors in the timescales of the Vostok ice core is less than 2 ka, the authors attempted to transfer the Vostok O2/N2 age (Suwa and Bender, 2008) to the EDC core. The authors claim that the age transfer error by radar data is within several hundreds years. Then, they claim that the time scale of the EDC core can be improved in 126 ka-247 ka age interval.

In our Glaciology community, many researchers have accepted an idea of isochronous nature of the radar internal layers. But at the same time, there were many examples of failure of transferring a timescale from one existing ice coring site to future candidate sites. Such failure have occurred both in East Antarctic sites and Greenland sites. We have recognized errors much larger than the authors of the radar papers had claimed only after ice coring was completed at EDC, NGRIP and NEEM. In the review process, no critical views worked in the cases of the past.

My major concern to the present paper is highly plausible underestimation of errors and uncertainty. The authors synchronization work was done basically independently from real ice core signals. But we see that a few papers are already available to synchronize between Vostok ice core and EDC core (Delmonte et al., 2004;Parrenin et al., 2012). These two kinds of signals agreed well with each other. Disagreement between the radar-based tie points and the ice-core-based tie points are often well above 20 m. See Figure 1 of this review (next page). The sign of the disagreement is both plus and minus. Thus, we cannot see nature of errors as simple systematic errors. In addition, if we transfer Vostok age scale to EDC core based on ice core tie points, the discrepancy between radar-synchronization-based age and the core-synchronization-based age sometimes exceeds 6 ka (see Figure 2 in this review). I suggest the authors try by themselves to check the Figures 1 and 2. And, if my analysis is correct, I suggest the authors to reconsider their claim of the very small errors and low uncertainty. My view is that the authors' recalibration of the EDC3 time scales is not practically useful. More detailed comments are listed below.

In this study, our aim is to obtain a precise stratigraphy for the radar layers connected between the two core sites. We use for this eleven radar layers sampled regularly through the ice column and chosen on the basis of continuity and bright reflections. 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 (chosen so) which is a function of the range resolution but also of the signal to noise ratio (SNR) for each radar layer depth considered. The SNR is what determines how precisely we can identify the peak of a radar return, i.e. our radar layers. We call this depth error "radar layer range precision error σ_{r^*}".

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

We then consider other sources of error (detailed and discussed in the paper's new error analysis section 3.2) that could impact our radar range precision error: temperature, impurity concentration and crystal fabric can all contribute to wave velocity in ice variations, a firn correction error is included for each ice core site radar line crossing.

We reproduced Figure 1 (see here below), with in red our radar layers, in magenta, the Delmonte et al study and in blue, the Parrenin et al volcanic study. We focus on the penultimate glacial cycle, for the reason that potential aeolian processes have corrupted radar layers belonging to the last glacial cycle. We agree that the disagreement between the radar-based tie points and the ice-core-based tie points are on the order of 20 m. However, for a meaningful comparison of the two core synchronizations, we would need to know the depth errors involved in measuring dust peaks in the Delmonte et al study (2004). 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."

No depth errors were given in measuring the dust peak depths in the Delmonte et al study. Both the radar-based and the dust-based tie points under-sample the depth-depth stratigraphic relationship between the two ice cores: both are linearly interpolated between discrete points measuring depth differences between two under-sampled curves. With uncertainties measured only for one of the two correlation methods, a comparison of the depth-depth curves is not meaningful at this stage. Based on the uncertainties only, we argue this comparison is not solid enough to reject an uncertainty quantification approach that is as grounded in the geophysical radar remote sensing literature as the approach described in the supplemental material.

In addition, we plot the maximum and the minimum dielectric constant values obtained for these two ice core sites (3.13 – 3.19), represented as thin grey lines on Figure 1 here below. The fact that these plot so closely to our radar tie points shows how robust our results are with respect to dielectric constant errors.

We reproduced our Figure 2, using our new radar layer depth errors and total age uncertainties: our synchronized Dome C radar layers now all plot within the (Parrenin et al, 2007) EDC3 published age uncertainties and our calculated total radar layer age uncertainties.

This seems to validate our calculated radar layer age and depth uncertainties.

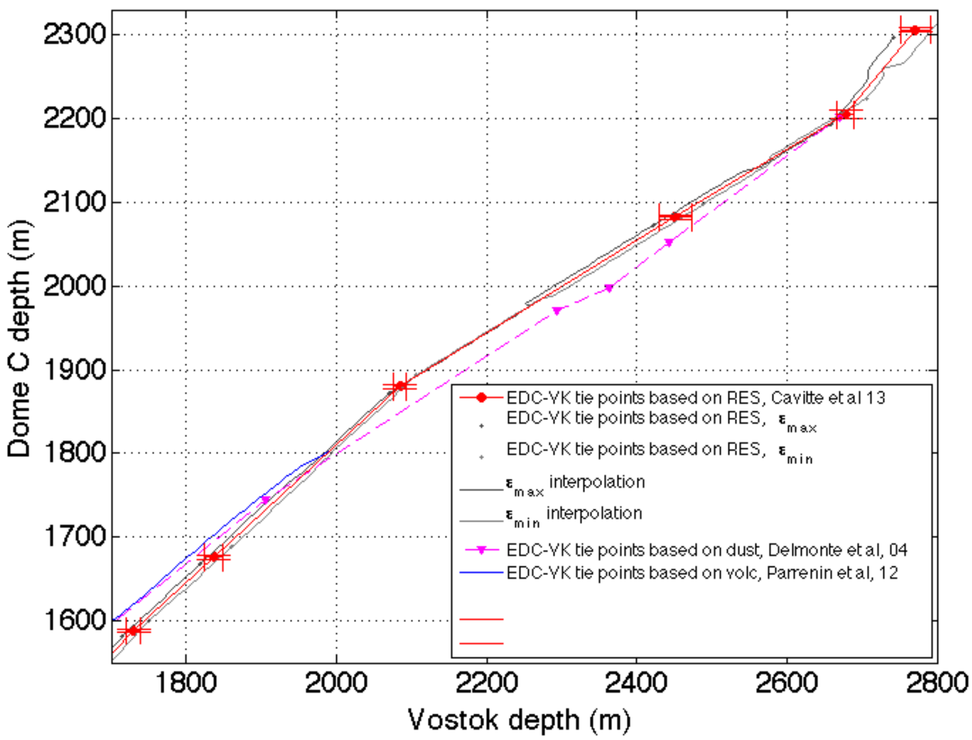

Figure 1 reproduced: stratigraphic tie-points between Dome C and Vostok ice cores via three independent techniques. In red, the radar tie points (this study), with the associated radar layer depth error estimates at Dome C and Vostok sites represented by the red error bars; in magenta, the dust tie points (Delmonte et al., 2004); in blue, the volcanic tie points (Parrenin et al., 2012). The gray bounding curves around the radar tie points represent radar layer depths for the maximum and minimum dielectric constant values used. Note how close these two curves plot around the red radar tie-points curve.

Detailed points

Title of the paper

It seems to me that constraints were not given successfully.

Has been changed to reflect the new focus of this paper.

Abstract

P.322, L. 6: Radar depth uncertainty is much larger than the authors claim here.

Layer depth uncertainties have been changed to reflect the new uncertainty measurement approach.

P. 322, L. 11: Meaning of the "resolution of the ice core age" is unclear.

Re-worded.

1. Introduction

P. 322, L. 17: Citation is not proper. Bender (1994) never represents EDC ice core project.

Changed to EPICA community members, 2004.

P. 322, L. 21: The paper should be Suwa and Bender, and not Bender and Suwa.

Changed

P. 322, L. 26: Rather than "validating" or "recalibrate", ice core researchers have used wording of "synchronization" so far in many papers. I believe that the latter is better wording because we can never say that dating of the Vostok core is much better than EDC core.

We agree and have changed to using “synchronization”.

P. 323, L.10: It seems that point (1) was not properly demonstrated so far.

Point (1) was taken out from the introduction, as the referee is correct in that this has not been demonstrated robustly in similar radar studies, and we develop this idea later in the discussion.

2. Data and methods

Figure 1: Show to readers pulse width used for each radar measurement line. In the present manuscript, this information is not given.

It has been changed so that two different colors represent the two radar systems: black for coherent, dark magenta for incoherent (see figure caption too).

P. 323, L.17: When you mention pulse widths, show to readers equivalent widths in ice already here.
These long pulse widths of 250 n-second (~21 m in EM wave in ice) or 100 n-second (~8m in ice) should be explicit.
This has now been changed to show the equivalent pulse resolution in ice. Quoted pulse width values have been changed to reflect the pulse widths as measured directly on the radar layers on the transects intersecting the ice cores, which should give the most relevant pulse width values for this study. These are now 100 ns and 290 ns for the EPICA Dome C and Vostok transects, respectively.

P. 323, L.25: Readers will understand that the authors used some commercial software. But then readers cannot see how reliably the authors determined the layers. The authors must how much were the errors when they chose different routes of the radar transects, as statistic points of view. Also, demonstration of A-scopes indicating tie points will help for better understanding by readers.
This radar correlation uses a set of radar transects which are gridded in some parts, but ultimately, a single line connects the two cores. We therefore cannot compare different route statistics. But in order to assess our depth uncertainties and the uncertainties associated with radar line crossovers, we calculated absolute depth differences for a same layer between intersecting radar lines. These were all about a half of our quoted radar layer depth uncertainties. We are therefore confident that we traced a same layer from core to core throughout the radar survey. This gives us added confidence in the depth error bounds we calculate.
Table S1 provides crossover errors for each radar layer, as well as our radar layer depth errors for comparison.
We plot A-scopes with tie points for two intersecting radar lines, shown here below in Figure 3. However, we feel that providing a table of our crossover errors is more

helpful to the readers and therefore do not include Figure 3 in our paper or supplements.

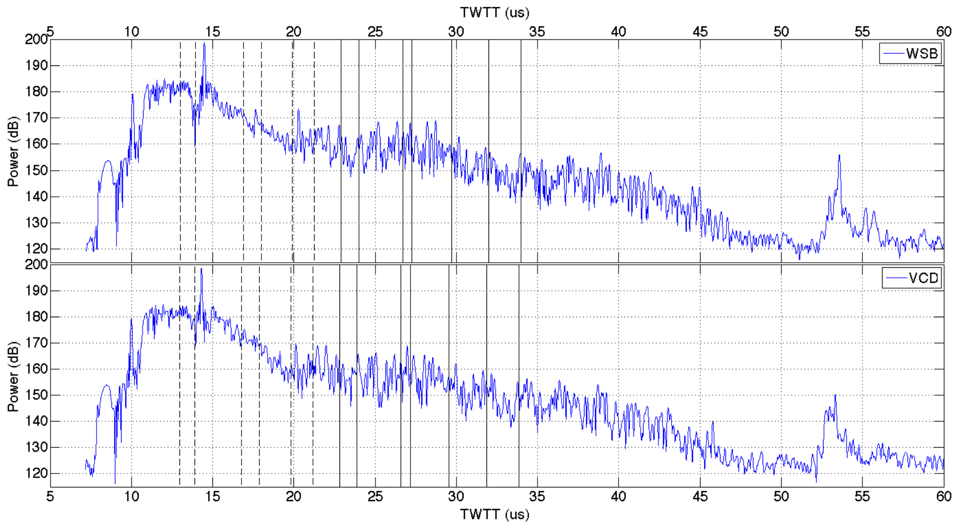

Figure 3. Plot of A Scope data for two intersecting radar lines (labeled VCD and WSB) with our radar layers plotted as black lines. Dashed lines correspond to last glacial period; full lines correspond to the penultimate glacial period.

P. 324, L. 2: The refractive indices of ice is dependent on both ice temperature and crystal fabric. The authors must give error estimates on how much are errors caused by the assumption of the constant wave velocity. If error is not negligible, effects on both ice temperature and crystal fabric must be used in analysis.

Errors associated with temperature, crystal fabric, impurity content are now folded into our radar layer depth errors. 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/us 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/us.

-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 higher than for polar ice. We obtained C_{ice} = 168.5±0.20 m/us.

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 also been added (Section 3.2).

3. Correlating Dome C and Vostok

P. 324, L.7-10: Results are given suddenly. Readers need to see potential errors. See my comments for P. 323, L.25.

Errors are discussed in the section just below. We felt it would be easier for the readers to first describe the radar layer correlation obtained to appreciate the importance of the error analysis better. See a discussion of potential errors in comment just above.

P. 324, L.14-19: Readers will not understand how much errors occurred in the previous attempt of the radar synchronization by Siegert et al. (1998b). We see just an excuse here.

The radar synchronization obtained by Siegert et al. (1998b) involved a substantial 150 km gap between the radar transect where layer depths were traced and the ice core site where layer depths were calculated. 150 km represents almost a third of the distance between the two ice core sites, and due to the sloping surface topography and complex bedrock topography in the area (Tabacco et al., 2006), we argue assuming horizontality of layers over such a large distance would cause significant layer depth errors. This was stated in the paper as a significant source of error. We have now attempted to make this clearer to the readers in the paper.

P. 325, L.15: Why vertical resolution is 30 m in Vostok using the pulse width of 250 ns? It seems to me that 30 m is equivalent to ~350 ns in ice.

A typo was made when quoting the incoherent radar system pulse width. It should have stated 350 ns, for which we had originally calculated the 30 m depth resolution. We have now revised the pulse widths to the measured radar layer returns, see (P. 323, L.25) reply to comment.

P. 325, L.16: The authors claim that the picking accuracy is within one tenths of the pulse width. This claim is not credible. Radar layers are interference pattern of the all reflections within a pulse. Basically, depth of each single reflector is not resolvable.

We have now calculated these radar depth errors more accurately; a detailed discussion rooted in the astronomy literature is provided in our Supplement 1.

In measuring the depth of a layer, we are interested in the range precision i.e. how well we can identify the peak of a radar return, taking into account the noise levels in the data for the different radar layers considered. This is a function of our radar vertical resolution (the interference patterns over a pulse width) and of the SNR of each of the radar reflectors considered.

We call this depth error "layer range precision error σ_{r^*}". The maximum and minimum precision errors are given in Supplement 2 for each ice core site crossing.

Table 1: The claimed Z errors seem too small than real size of errors. In earlier papers of the radar sounding using pulse as large as 250 ns, I have not seen any examples of demonstration about small Z errors like this table. Even if we use pulses less than 100 ns, errors of a few meters naturally occur. It seems to me that underestimation of errors is the major problem of the present work.

Radar layer depth errors have been changed and now show the full depth errors which are a combination of the radar system range precision error, firn correction error, as well as wave velocity variations due to temperature, fabric and impurity concentration variations. See discussion of range precision errors and depth errors in our comments above.

P. 326, L. 28-27: The authors mention that errors in ice core dating are for absolute ages. Errors for synchronizations are for transferring dating markers from one core to another. Nature of the errors are different. This point must be clarified to readers.
We agree, this point has now been clarified.
We differentiate between relative radar layer age uncertainties which arise from the radar system depth errors, and total radar layer age uncertainties, which are a combination of the relative radar layer age uncertainties and the ice core published age errors.

P. 327, L. 1-2: It is not a fair emphasis that age discrepancy is less than 1 ka at a single very deep tie point. The other shallower tie points have much larger errors. In addition, the agreement of a single point may be just accidental.
We agree this was too strong an emphasis and this has been removed from the discussion. It remains that the layers used to correlate the two ice cores reach very large depths, as close to the echo-free zone as was allowed to retain layer tracing accuracy.

P. 327, L. 3-17: The discussions need to be reconsidered totally. It seems not fair to give most of error causes to ice core dating. Ice core tie points in this review are against the view of the authors.
We have now revised the discussions to reflect our new uncertainty measurements and the new handle this gives us on the potential of such radar correlations.
See earlier general comment section for discussion of ice core tie points.

4. The EDC3 timescale

For me, there seem various errors in transferring the O2/N2 age markers from Vostok core to EDC core. Suwa and Bender (2008) gave variation of the gas O2/N2 profile. But they did not explicitly provide errors at the depths of the O2/N2 marker points and interpolated depths. Ice core dating is done only by combination of reliable age marker and the ice core modeling for the best interpolation among age markers. See Kawamura et al. (Kawamura et al., 2007) paper on this point. They very carefully assessed errors around the tie points and the interpolated depths based on ice sheet modeling. The authors of the present paper just linearly interpolated age markers of the gas O2/N2 profile without assessing error for each tie point. I observe no careful handling of errors at this beginning.

We used the published Suwa and Bender (2008) O2/N2 age uncertainties given in their paper. To the best of our understanding, they quote only two conservative error ranges of ± 1 and ± 2 ka for the radar layer depths that we consider in this study. Independent assessment of the error accuracy in the Suwa and Bender (2008) timescale is outside the expertise of the authors of this paper.

Using pulse widths of both 250 ns and 100 ns causes errors as well.

In addition, I wonder how much is the error caused by wave speed in ice handled as constant value.

These pulse width-related errors have been assessed and calculated using the radar layer range precision errors and the ice core "age gradient" for each radar layer depth in the ice column (this is now described in section 3.2 of the paper). These age uncertainties are related to the radar system and provide relative age uncertainties that we term "relative radar layer age uncertainties". Ice core published age errors have to then be combined with these radar age uncertainties to give our total radar layer age uncertainties quoted in Table 1. The errors associated with wave speed variation in ice are considered in the radar layer depth errors and therefore are taken into account in our total radar layer age uncertainties.

When the synchronization is compared with ice core signals (volcanic and dust), the errors seem much larger than the authors claimed. I do not suspect here ice core signals easily because in volcanic synchronization, errors are within centimeter scales. Dust synchronization agrees well with the volcanic synchronization. In contrast, I find many reasons to suspect errors of the radar layer synchronization in the analysis of the present paper.

I believe that, some day precise radar synchronization between two deep ice core sites will be demonstrated. But at the moment, from my view, present paper is an example of claiming too small errors than reality.

Relative dust and volcanic marker correlation are very likely to share the same systematic (and unknown; Parrenin et al., 2012) errors; however, these relative errors comparisons are of limited value in absolute comparisons with the radar stratigraphy.

P. 328, L.15: The authors are providing just several age markers from Vostok ice core to EDC. The authors can claim to this stage of providing just several age markers. But they cannot claim validity of the linear interpolation within the EDC core. It is too rough for ice core dating.

We agree that the radar correlation provides a discrete number of connecting radar layers between the two cores. We linearly interpolate piece-wise between age markers for the very reason that attempting to connect the markers with some higher order polynomial would be aliased due to our under-sampling of the age-depth scale. However, linearly connecting our age markers this way makes the age-depth comparison more intuitive to readers when comparing the published EDC3 timescale and our radar synchronized data points.

P. 328, L.18: Parrenin et al. (2007) used total air content for constructing EDC3 timescales to depths of ~2700 m. Thus, d18O time scale is not proper expression. See caption of the Fig.2 as well.

Changed.

P. 329, Last paragraph: The authors claim that their synchronization agrees well with the Delmonte et al. (2004) dust synchronization. But for me, the comparison just showed errors much larger than the authors claimed.
See Figs. 1 and 2 in this review.
We use the Delmonte et al (2004) dust synchronization to qualitatively demonstrate to the readers that both correlation studies obtain the same stratigraphic relationship between the two ice cores. Their correlation shows dust markers at Vostok between the surface and a depth of 1120 m to be shallower than at Dome C and dust markers between 1120 m and 2200 m to be deeper.
See general comments section for discussion of the errors.

5. Conclusions

P. 330, L.4: No "continuous" synchronization was done. They are just for discrete 7 tie points.
We meant "with no breaks" in the radar lines from core to core. This has been changed.

P. 330, L. 10-11: No, traditional ice modeling is still very important for dating between reliable age markers.
In addition, comparison between ice core markers are the most reliable. The present work failed to demonstrate that the radar-based synchronization have very small uncertainly of the order of several hundred years.
We agree this was awkwardly worded: we meant that radar layers can be beneficial to ice core correlation exercises as an added independent measurement which contributes errors no larger than or equivalent to the ice core dating and modeling methods. This has now been reworded.
The new revised age uncertainties on the radar layers are a combination of the relative radar layer age uncertainties and the ice core published age errors and are therefore of the order of the ice core age errors, as radar methods can only provide "relative ages".

Other comments

Table 2 is repeating a part of Table 1. It seems unnecessary.

We feel Table 2 is important for the following two reasons:

1). The total radar layer age uncertainties are different from that of Vostok in Table 1 as they are the rms of the relative radar layer age uncertainty at Dome C and the total radar layer age uncertainty at Vostok, and so Table 2 allows the readers to easily see whether the uncertainties are strongly impacted by the Dome C relative age uncertainties.

2). The readers can visually see how each synchronized radar layer at Dome C (i.e. EDC3n) has a much smaller age uncertainty.

Fig. 6 provides nothing new visually.

We agree and have removed this figure. To show the difference between layers we observe that belong to the last glacial cycle and to the penultimate glacial cycle, we have added the EPICA Dome C timescale comparison plot for layers pertaining to the last glacial cycle only as Figure 5. The EPICA Dome C timescale comparison plot for the penultimate glacial cycle is now Figure 6.