Response to RC1: Validation of torus mapping method for dealiasing Doppler weather radar velocities

The authors would like to thank the Referee 1 for a very detailed review and constructive comments.

We agree with referee's remark that the main application was not highlighted enough. The main purpose of our work is to implement the torus mapping method for operational data assimilation, specifically for the ACCORD consortium, with the use of OPERA radar dataset. By validating the method against a large independent observation and model reference datasets, we want to demonstrate that the method is robust enough to handle radar observations from a very heterogenous source (OPERA) and provide dealiased data of sufficient quality for use in NWP. To highlight this goal, we propose a slight title change, to "Validation of torus mapping radial wind dealiasing method for use in NWP".

1. Responses to general comments

(1) • Yes, as mentioned above, the main focus of our validation is data assimilation of Doppler winds provided by OPERA programme by EUMETNET. It is a centralized repository for radar data from most European countries with various degrees of preprocessing and quality control provided by individual weather services. This results in a heterogenous set in terms of preprocessing, scanning strategies, radar configurations, etc., that also changes with time. For use in NWP assimilation, we therefore need a very robust method to handle this heterogenous set, without tuning for individual radars. It also should not rely on an external data source. As the intent is operational use, method must also be fast and use little CPU resources. We looked into existing methods and identified the torus mapping method as most promising for this purpose, as it has all the required properties.

- The torus mapping method is very similar (to the first order in $\Delta\theta$) to the V-IVAP method used by Liang et al. 2019, hereafter L19 (see answer 2 and section 4), so for sparse data (in the azimuth direction), the method works well, provided that the azimuth interval used in determining the reference velocities is as big as possible. That is why we used the whole interval (-180,180) in our implementation of the torus mapping method.
- For high shear in vertical direction, the method also works well (see figure 1), because data used in our implementation of the torus mapping is divided into 100 m height intervals, combining data from multiple elevations. For each interval, a separate reference velocity is calculated, allowing for any wind change in the vertical direction.

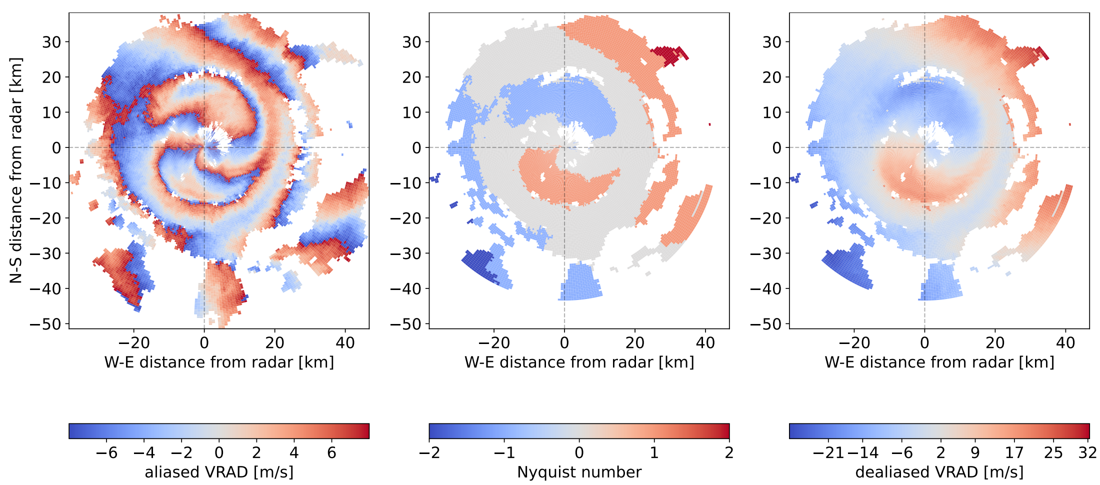

FIGURE 1. Dealiasing for a high vertical shear case on 4.June 2021 for an elevation with angle $6.3°$ on the Pasja Ravan radar.

- For high shear in the horizontal direction, the results of the torus mapping method are poorer (similar to the V-IVAP method) (see figure 2). It could be augmented by a secondary more local method as in L19, however, since we expect that the remaining incorrectly dealiased data from high shear areas would be filtered out by the background check as part of the quality control in data assimilation (figure 8 in paper), we do not employ this extra step to reduce computing time.

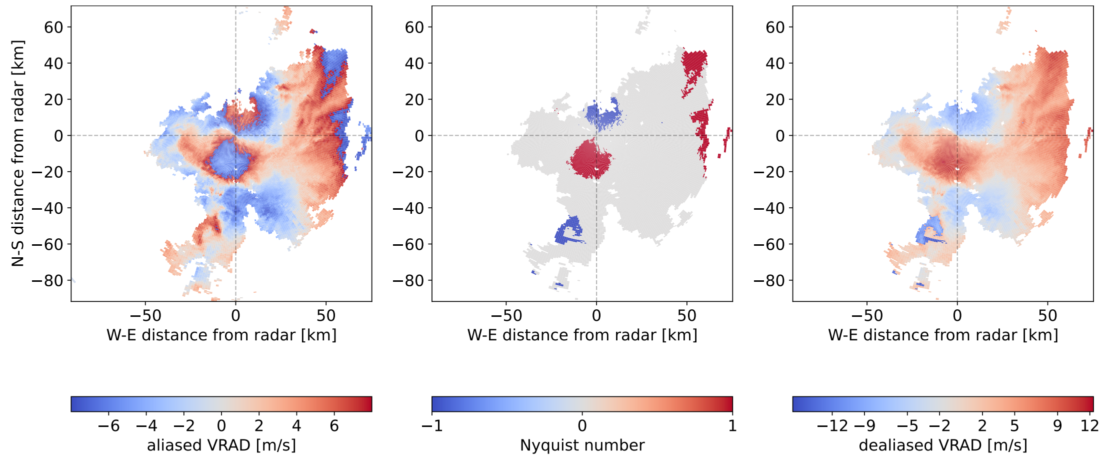

FIGURE 2. Dealiasing for a high horizontal shear case on 5.May 2021 for an elevation with angle $3.8°$ on the Pasja Ravan radar.

(2)

- As our focus is on a large scale validation and usefulness in assimilation, we did not seek to develop an entirely new method, but rather use an existing one and adapt it for use in assimilation. The reasons for choosing the torus mapping method are explained in (1). The decision to use torus mapping was taken in 2019, when the new V-IVAP/IVAP method by L19 was not published yet, but after a review of the suggested paper, we conclude that the torus mapping method is very similar to the V-IVAP method. In fact, if we expand equations (7) of L19 to the first order in small $\Delta\theta$ and express the azimuth derivative $(V_{r,\theta} - V_{r,\theta-\Delta\theta})/\Delta\theta$ (see section 4), we get the same equation from which the reference wind is determined in both methods (for torus mapping these are equations (5)-(8) in the paper). While we do not apply a second step for local corrections (as the IVAP method in L19), we show that using only torus mapping is enough for assimilation purposes.
- The OPERA programme does not provide any dealiased datasets, apart from radar networks that apply dual- or triple-PRF technique (DE,FR); for those countries,

data is still aliased on the extended Nyquist interval. As far as we know, in ACCORD no country applies dealiasing operationally. Dealiasing is used at the Swiss meteorological service, but these results are not provided to OPERA and a direct intercomparison is not possible.

(3)
- We agree with the referee that there is a discrepancy between radars introduced with figure 4 in paper and those used for validation as datasets A and B. For a detailed analysis, we wanted to focus on radar networks where aliasing of data is the main problem, to exclude as much as possible the sources of other nonrelated errors (such as noise), which mask the impact of the dealiasing on the results. However, the validation was done on all shown radars and we will provide analyses per radar network (country), further clarifying the selection of datasets for detailed analysis.
- As explained in (2), data from DE and FR are already provided on the extended Nyquist interval. Because we want the dealiasing method to be universal for all OPERA data, the errors that stem from the multi-PRF dealiasing are not specifically treated, but included in the analysis as all other possible errors in the width of statistical distributions.
- The SI dataset is indeed different from dataset A only by filtering for events, but is named differently to make the distinction as SI and DE datasets do not contain colocated pairs.

In figure 8 in paper, we mistakely included only colocated pairs. This will be corrected, as the assimilation procedure works on all data.

(4) Figure 3 in paper is just for illustration of the way our implementation of torus mapping algorithm rejects data, that is why values are not shown to emphasise the rejection, but we will provide explicit dealiasing examples for low Nyquist velocity (see figures 1, 2).

(5) Algorithm specifications and performance was indeed not put in the paper, but it should be and will be included in the paper. Algorithm was written in the Python 3.10 programming language. With it, we performed dealiasing on 10 random samples each containing around 50 3-volume HDF5 files taken from OPERA in the year 2021. The dealiasing was done on a HP EliteDesk 800 desktop computer, with an Intel Core i5-8500 3.00 GHz processor, 16 GB of DD4 RAM and 931 GB HDD. Processing time for one radar volume ranged from 1-15 s, depending on the amount of data contained in the file, on average the processing time for one radar volume was around 3 s.

2. Responses to specific comments

(1) Thanks, will be corrected.

(2) We will include the recommended (more recent) advances and expand this section.

(3) We apply linear wind assumption on height intervals (of 100 m). However, we apply the same assumption to the whole azimuth interval, as we want the method to work also for sparse data as explained in answer to general comment (1). In this, we are similar to the V-IVAP method of L19. A local method is not applied, also explained in answer (1), dealing with high-shear situations.

(4) As explained in answer to general comment (2), the torus mapping method is equivalent (to the first order in $\Delta\theta$) to the V-IVAP method of L19 (which is based on VAD), by using azimuthal variances (azimuthal derivative) of radial velocity to retrieve reference winds.

Compared to L19 V-IVAP implementation, we use the whole azimuth angle interval, with 100 m height levels, 60 m/s threshold on the reference wind. We also do not reject VRAD values below 1 m/s to retain valuable information for data assimilation and do not perform the interpolation from radar coordinates to lat-lon grid and back. We also do not apply the IVAP method step afterwards as explained in answer to general comment (2).

(5) Torus mapping is sensitive to noise and performs poorly if the amount of noise is high as shown with a small example. Because of this we recommended denoising before using the method to dealias data.

The method only has poor performance in horizontal high shear situations such as frontal boundaries and high turbulence situations. As the target application is assimilation, we show that small-scale errors done in these cases will most likely be filtered out by the quality control of data assimilation (also see answer to general comment (1)).

(6) You are correct, we use data from all elevations that fall inside a specific 100 m height interval for determining the reference wind. By using OPERA data, which has data files grouped in 15 min intervals, this means that we use data from multiple consecutive volumes contained in the file (e.g. 3 volumes of 5 minute measurements). This also coincides with our time window used in colocation and the current needs for data assimilation in terms of observation frequency.

(7) As mentioned in answer to general comment (3), we performed the validation for all countries, but chose specific radar networks that have aliasing as their main problem for the detailed analysis. This is done to show the impact of just the torus mapping dealiasing on data without masking the impact with errors from other sources.

As explained in answer to general comment (2), most ACCORD countries do not deliver dealiased data to OPERA, apart from multiple-PRF Nyquist interval extensions.

(8) All radar networks that lie inside our NWP domain were introduced, however, only the ones included in datasets A and B had the aliasing of data as the main source of error (see also answer to general comment (3)). The validation was done on all networks, so we will provide a summary of results for all radar networks to show why the detailed selection was made.

(9) Thanks, the figures will be corrected.

(10) Indeed, the hatching in the panels is not optimal for clarity and will be corrected.

(11) Yes, we only used log scale for dataset B for easier visual interpretation as there, data is less aliased. The use of log scale for dataset A would highlight additional peaks at multiples of Nyquist velocity, so we will use log scales for all figures.

(12) Thanks for pointing out this error. It will be corrected.

(13) We agree with this statement, and will rephrase the sentence and include a summary of analyses for all radar networks that have been excluded, to justify their exclusion.

(14) Acceptance rate as used in the manuscript is the ratio of accepted and all data that enter the data assimilation. It is a function of the dealiasing method applied but also of the assimilation quality control used. So it is difficult to compare this rate by only comparing dealiasing methods.

Dealiasing failure rate is based on an assumption that all aliased data is contained in the side peaks of the difference distributions, against other observations or NWP model. After the dealiasing, the peaks reduce roughly by a factor of 10, which means that 10 percent of initially aliased data remains aliased after applying torus mapping. This can be taken as an estimate of the failure rate.

Compared to failure rates of methods from the recommended literature, this rate is much higher, but it has to be noted that in these methods, failure rates were estimated in a controlled, idealized framework, where references used for truth (S-band radar, model results) were artificially aliased. While this is of course a good methodology for evaluating the theoretical failure rate of a method, we chose the mentioned rough estimate as we do not have a proper truth reference so there are additional factors contributing to the failure rate estimate (NWP errors, measurement errors, natural variability between colocated points). As shown in figure 8 in paper, the failure rate can be compensated by using stricter quality control in assimilation.

(15) Because of these fundamental differences, we compared measurements using statistical distributions of colocated pair differences from large samples. This is often used in data assimilation to estimate quality of new observations without knowing the exact

sources of errors, as the distribution widths for pair differences contain all sources of errors from both measurements in an equal manner. This is also the reason that we used aircraft-sonde pairs as reference in figure 5 in paper, as both are already established measurements used in data assimilation.

The number of folds was examined on a spatial map, as seen in the middle plot of figures 1 and 2.

(16) The denoising was not applied for this analysis, but we demonstrate that it has a big impact on results in case it is centered around zero (e.g. ground clutter). We recommend that in this case, denoising should be done before using the torus mapping method. High-noise levels in data is also one of the reasons why we exclude such datasets from a detailed analysis, as an analysis of such a dataset would not show the effects of the dealiasing, but would be dominated by errors from the noise, to which the torus mapping method is sensitive.

For multi-PRF data with specific noise type, dealiasing is shown to be suitable as can be seen in figure 7 b) in paper, where we have results for DE dataset with dual-PRF.

(17) Thanks, will be corrected.

(18) We chose the torus mapping method, because it is robust, fast and works well for a wide range of situations and radar configurations. It's downside is that it has a poorer performance in horizontal high shear cases, but it nevertheless provides a large increase in number of available wind observations for general data assimilation. As explained above in answer to specific comment (14), the failure rate is estimated differently as in Louf et al. and Feldmann et al and is thus not comparable.

3. Revision of paper

Given the very relevant questions raised by Referee 1, we propose a revision of the paper, where we would:

- Since the purpose of our work is to show that the torus mapping method provides dealiased data of sufficient quality for use in NWP, we will make a slight change in the title and revise the text of the paper to make this purpose clearer.
- We will include more recent references that Referee 1 suggested, with more discussion and compare our method to the similar V-IVAP method.
- We will include individual case studies to show the performance of the algorithm in high shear cases.
- To explain our choice of datasets, we will include analyses from all radar networks and justify our reasons for choosing a subset of data for detailed analysis and revise the text accordingly.
- Improve algorithm implementation description (performance, specifications).
- Correct the figures and other smaller errors as suggested.

4. Comparison of reference wind equations

In L19, their equations (7) are used to determine the components of reference velocity ($\overline{u}$, $\overline{v}$). In the equations, we can simplify expressions if we assume $\Delta\theta \equiv d\theta \ll 1$:

$$\cos\theta - \cos(\theta - d\theta) \approx -d\theta \sin\theta, \qquad \sin\theta - \sin(\theta - d\theta) \approx d\theta \cos\theta,$$

If further define $dV_{r,\theta} \equiv V_{r,\theta} - V_{r,\theta-d\theta}$, and use the simplified expressions in their equations (7), the first equation becomes:

$$\sum_{\Omega} dV_{r,\theta} d\theta \cos\theta = \overline{u} \sum_{\Omega} (d\theta)^2 \cos^2\theta \cos\phi - \overline{v} \sum_{\Omega} (d\theta)^2 \sin\theta \cos\theta \cos\phi,$$

and the second equation of (7) is identical to the first. Now we can express the azimuth derivative of radial velocity:

$$\sum_{\Omega} \frac{dV_{r,\theta}}{d\theta} = \sum_{\Omega} (\overline{u}\cos\theta - \overline{v}\sin\theta)\cos\phi.$$

To obtain the reference velocities in the torus mapping method, we minimize the square of differences between LHS and RHS of our equation (5) for a chosen subset of data:

$$\sum_{\Omega} \frac{dF_{3,r,\theta}}{d\theta} = \sum_{\Omega} (-a\overline{u} + b\overline{v}),$$

where we now use the same notation as in L19 for easier comparison.
The derivative $\partial F_3/\partial\theta$ can be expressed from our equation (4):

$$\frac{dF_{3,r,\theta}}{d\theta} = -\sin(V_{r,\theta}\frac{\pi}{v_{ny}})\frac{dV_{r,\theta}}{d\theta}.$$

If we insert this into our equation (5) and use our equations (6) and (7) for coefficients a and b, we get:

$$\sum_{\Omega} \frac{\partial V_r}{\partial\theta} = \sum_{\Omega} (\overline{u}\cos\theta - \overline{v}\sin\theta)\cos\phi.$$

So theoretically, both methods use the same relation (to the first order in $\Delta\theta$) to determine the reference velocity. Of course, the differences are in implementation; L19 solves a system of two equations, while we use a least squares minimization approach. Second difference is in the numerical method of derivative calculation, above we see that in L19, the method would be left differences, while we use central differences. The third difference is, that the torus mapping method does not numerically calculate the derivative $dV_{r,\theta}/d\theta$ directly, but calculates $dF_{3,r,\theta}/d\theta$, which contains an extra factor of $\sin(V_{r,\theta}\frac{\pi}{v_{ny}})$.