Author's response to:
RC#2 from Anonymous Referee #2
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Dear Anonymous Referee #2,

We want to thank you for your suggestions and the thorough evaluation of the manuscript. We revised multiple parts of the previous submission and added more details, mostly according to the reviewer's suggestion. This revised version provides a better explanation of the used methods and results.
Thank you for carefully reading the manuscript and pointing out several issues where the description needs to be improved for understanding. The requested clarifications and references to ambiguities contribute to the improvement of the manuscript.

In order to separate the reviewer's comments and the author's response, we printed the comments in black and the response in blue. Excerpts of the manuscript with marked changes are pinned directly to the appropriate responses, with the indicated text location (e.g., line number) referring to the manuscript in preprint.

Sincerely, on behalf of all authors

Heike Kalesse-Los

Changes done to the manuscript:

- The Virga-Sniffer code was updated (v0.3.4 -> v1.0.0), with mostly minor changes (e.g., more flexible plotting routines). Nevertheless, there are two considerable additions, listed below. In particular, the handling of situations in which precipitation falls into lower cloud layers was changed compared to the first submitted manuscript. We now focus on avoiding misclassifications and therefore set the newly introduced configuration *cbh_connect2top* to False (see below).

  1. Adding a configuration flag "*lcl_replace_cbh*". When additional LCL data is provided, this flag changes the behaviour of the *add LCL* module for CBH preprocessing. In the default setting (True), the LCL data completely replaces the lowest ceilometer CBH layer. If False, the LCL data is merged with the lowest ceilometer CBH layer by replacing only missing values.
  2. Adding a configuration flag "*cbh_connect2top*". This flag changes how situations where precipitation falls in lower CBH layers are handled. In the default setting (False), the lowest CBH is retained and higher CBH layers are omitted from processing because no distinction can be made between clouds and precipitation from higher layers if there is a continuous radar signal in the profile. Therefore, the default setting is most conservative to avoid false detection of virga. For True, the top CBH layer is retained and the lower CBH layer is omitted from processing. This approach results in more precipitation data points, but it is prone to misclassification of cloud droplets as precipitation.

  The up-to-date version of the Virga-Sniffer is hosted on GitHub, see also its Changelog (Witthuhn et al., 2022). All results and figures have been updated according to the new version.

- The technical description of the Virga Sniffer (Sect. 3) has been significantly revised. Care has been taken to name optional data and default configurations explicitly in order to avoid ambiguities. In the course of this, the flowchart (Figure 2) and the illustration (Figure 3) were adapted.

- A new appendix (B) has been added, where the sensitivity of precipitation and cloud detection on setting parameters and optional data are analysed and discussed.

- In section 4.1, "Comparison with Cloudnet target classification", we have added another performance evaluation of the *Virga-Sniffer*. Here we analyse how many data points were evaluated as precipitation by CloudnetPy but not by the *Virga-Sniffer*.

- Many text passages, figures and tables were revised in consideration of review comments, as can be seen in the detailed responses.

Response to RC#2 of Anonymous Referee #2:

General Points

There are a large number of thresholds used within the study, how sensitive is the output of the virga-sniffer to these thresholds? Some discussion of the parameters that the tool is sensitive to is necessary. Why are they set at their current values? How does changing them effect the results?

To address this comment, we added a new Appendix (B). In this Appendix, the effects of the Virga-Sniffer setting are discussed. Also, the sensitivity of the setting parameters is studied versus their default values, by comparing the number of data points and time-steps for which virga and clouds are detected.

There is some mention that the tool works without the inclusion of the LCL and the surface precipitation measurements. Some discussion of the differences in the results with and without these parameters would be useful.

Yes, the inclusion of LCL, surface precipitation measurements and mean Doppler velocity are optional. The new Appendix section (B3) addresses how the detection is affected when not using the optional data.

Minor comments

1. ***L98:*** *Are roll and pitch angles allowed to be negative? If so replace this with absolute angles. If not, why is the standard deviation so much greater than the mean, this implies a very skewed distribution?*

* Yes, the attitude angles can be negative. We redid the calculation of the mean and standard deviations using absolute values as suggested. The mean and standard deviation of the pitch and roll angle then amounted to $0.36 \pm 0.31°$ and $0.19 \pm 0.16°$, respectively. We have changed the corresponding line in the manuscript:

L98f:
observed ~~roll and pitch angles experienced by the radar generally were less than $0.09 \pm 0.49°$~~absolute values of roll and pitch angles experienced by the radar generally were less than $0.36 \pm 0.31°$

2. ***L100:*** *Together with the previous point, if there is a sizeable inclusion of horizontal wind the pointing is relevant for the Doppler velocity. Is there any treatment or removal of Doppler velocity at large roll/pitch angles?*

* True, for large radar mispointings from zenith and high horizontal wind speeds, the influence of horizontal wind on the observed Doppler velocity is non-negligible. We do not account for this. Based on the radiosoundings, we did however do an analysis of the horizontal wind profile, for the relevant altitudes below the trade inversion height, the mean horizontal wind speeds had means of 5–8 $\mathrm{m\,s^{-1}}$. As stated in the manuscript, the highest Doppler velocity resolutions of the used chirp programs amounted to 5 and 5.7 $\mathrm{cm\,s^{-1}}$. The effect of the influence of horizontal wind on mean Doppler velocities for different radar mispointing angles is shown in Figure 1 of this reply. When considering the experienced values of roll and pitch angles (see answer to previous question) as well as the Doppler spectra resolution and the horizontal wind speed profiles, we conclude that filtering large attitude angles should not be needed often anyways. In

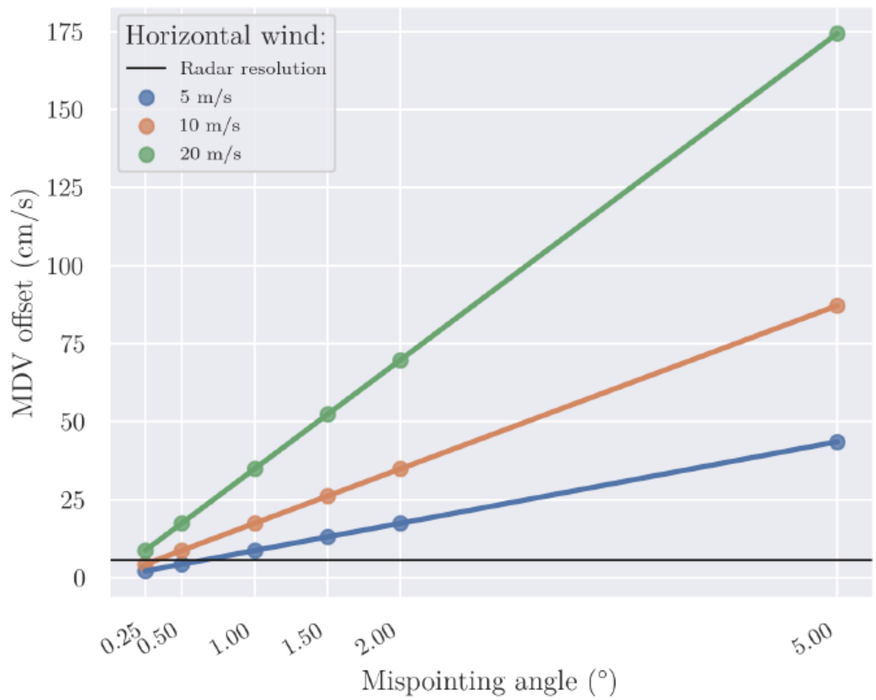

Figure 1. Influence of horizontal wind on mean Doppler velocity (MDV) caused by radar mispointing from zenith. Radar Doppler spectra resolution of $5.7\,\mathrm{cm\,s^{-1}}$ is indicated by black horizontal line.

fact, for mispointing angles less than 0.41°, no effect of typically experienced horizontal winds of $8\,\mathrm{m\,s^{-1}}$ magnitude are discernable in the radar Doppler spectra.

3. ***L196-198:*** *In this situation it is possible to have rain from another section of cloud blown in to the column and giving the impression of rain reaching the surface. Any consideration of this situation? Use of horizontal wind e.g.?*

* We agree, that the handling of tilted fall streaks in the Virga-Sniffer is one of the biggest challenges. In the current state, this is addressed by the implementation of the "*precip_max_gap*" threshold, which enables detection of precipitation which is not directly attached/connected to a detected cloud base. Of course it might happen, that a fall streak resulting in rain at the surface "enters" the profile just below the lowest radar range-gate (approx. $300\,\mathrm{m}$) in which case, the proper virga event above the fall streak with rain will be masked out. We have added another sketch as panel (b) to Fig. 3 and the following text pieces to address this situation:

L183ff.:
Precipitation is detected at each range-gate of ~~valid radar reflectivity~~ the radar reflectivity mask iterating downward from CBH until a gap ~~(nan-value in radar reflectivity)~~ occurs, which is larger than the threshold *precip_max_gap* of 700 m per default (see Appendix A). This threshold is large by choice, to also capture precipitation which can be observed from fall streaks advected to the radar viewing volume by wind shear. At the same time, the threshold is still small enough to mask out any clutter or unidentified clouds close to the surface or a lower cloud layer, respectively. Since the detection of clouds and precipitation with the *Virga-Sniffer* is carried out for individual profiles and no horizontal linking (in the temporal sense) of these profiles takes place, the handling of fall streaks is one of the most challenging aspects and is realized exclusively by the threshold value of the allowed gap size.

L208ff.:
Figure 3 panel (b) demonstrates how rain flags influence the precipitation or virga detection. Since radar observations only provide data at a certain distance from the ground, there may be an offset between the rain flag observed on the surface and the rain flag obtained from the radar signal. The user is given a choice, but additional input data is required for the surface rain flag. In Appendix B3 it is shown how the choice of rain flag affects the virga and cloud detection based on the EUREC^{4}A dataset. In addition, Figure 3 panel (b) again shows the influence of the choice of the threshold for the maximum permissible gaps for the detection of precipitation and the handling of fall streaks.

4. ***L199:*** *How frequently do these special cases occur and how frequently does the virga detection work with little or no complications?*

* Thank you for your comment. The use of "special cases" may not be appropriate in this context or may be misleading, as Figure 3 shows cases that occur all the time. While the column at time-step=1 can be seen as a standard case where no further considerations need to be made, the other columns show "special cases" to describe how gaps in the radar signal are handled. However, this kind of gaps appear very often. Therefore, we changed the text to be more specific, see below. Also, Figure 3 now includes a 7th column to demonstrate the handling of multi-layer clouds.

L199ff.:

Virga and cloud detection is sketched in Fig. 3 to ~~highlight special cases and usage of certain thresholds . Special cases~~ demonstrate the usage of thresholds handling gaps in the radar reflectivity signal. The specific cases of Fig. 3 panel (a) are:

- *time-step* = *1*: The standard case, when precipitation and cloud are detected from the observed CBH. No further considerations have to be made.
- *time-step* = *2*: The gap (range-gate (rg) 7–8) is smaller than maximum allowed gap for virga (*precip_max_gap* = 700 m) to count rg 6 as virga, but rg 6 is filtered since the requirement of minimum ~~virga~~ length of 2 rg is not met~~.~~, which is a requirement of the virga mask refinement based on the threshold *minimum_rangegate_number* (see Sect. 3.4 and Appendix A).
- *time-step* = *3*: The gap (rg 7–8) is smaller than the threshold, therefore rg 3–6 are counted as virga.
- ~~*time-step* = *4*: The~~ In addition, the gap (rg ~~7–11~~17–18) is larger than the ~~threshold,~~ maximum allowed gap for clouds (*cloud_max_gap* = 150 m) therefore rg ~~3–6 are~~ 19 is not counted as ~~virga. In addition, the~~ cloud. In this case, rg 19 could be a cloud, but since the *Virga-Sniffer* detection is tied to the CBH input data, rg 19 cannot be identified. Missing information about the second cloud layer can occur if the ceilometer signal is strongly attenuated by the clouds of the lower layer or by strong precipitation.

- *time-step* = *4*: The gap (rg ~~17–18~~7–11) is larger than the ~~maximum allowed gap for clouds~~threshold, therefore rg ~~19 is~~ 1–6 are not counted as ~~cloud.~~ virga. Therefore, the rain flag at the surface has no effect, as the virga detected in rg 12–14 does not reach the first rg.
- ~~*time*~~*time-step* = *5*: ~~Rain is observed~~ Precipitation is detected from (rg 1–14) as the gap (rg 7–8) is smaller than the threshold. Due to the rain flag at the surface (either by the additional data of surface rain flag, or by exceeding the radar reflectivity threshold in the lowest ~~rg)~~radar rg, ~~therefore~~ *ze_thres* = 0 dBz), no virga is assigned in this profile.
- *time-step* = *6*: Same as *time-step* = *5*. In addition, the gap (rg 17) is smaller than the maximum allowed gap for clouds, therefore rg 18–19 are counted as cloud. The surface rain flag doesn't lead to a reclassification of the detected virga towards rain, as the first rg has no data.
- *time-step* = *7*: Same as *time-step* = *6*. In addition, another CBH layer is observed right below rg 19. This CBH layer is not considered, as the gap at rg 17 is smaller than the maximum allowed gap for clouds, and it is not possible to distinguish between clouds and precipitation due to that. Therefore, the lowest CBH is assigned, as in time-step = 6 to initialize the detection of clouds and precipitation and the higher CBH is ignored per default (*cbh_connect2top* = False).

5. ***L201:*** *Is this step included when the clutter filter described earlier is also in use? Is it necessary if there is already a clutter filter?*

* In Figure 2, time step 2, range gate 6 shows an isolated radar signal. This may or may not be clutter. In Virga sniffer, clutter is defined by the combination of high mean Doppler velocity and low radar signal, which is not always the case even for signals from isolated range gates. This signal at range gate 6 could just as well be a signal from precipitation blown into this column by the wind. At least for the EUREC4A dataset, we found that single isolated signals from a range gate often appear near the lowest range gates, which are likely clutter but which we cannot verify and whose combination of mean Doppler velocity and radar reflectivity value for the mask_clutter step does not fall under "clutter". Therefore, we introduced a minimum number of contiguous range gates within a profile. We reordered the text of Sect. 3.3 for clarification and clarified the intention to mask clutter.

L210 ff.:

~~As a first step of virga mask refinement, virga events of each profile spanning less than two range-gates are excluded to remove false positive detection due to clutter (see Fig. 3, *time-step* = 2~~
~~). In addition, clouds and virga~~ Clouds and precipitation detection solely based on radar reflectivity and CBH is refined by using additional data of mean Doppler velocity and surface rain flag.
[...]
A data point is considered virga only if Eq. 1 is fulfilled. With default configuration (m = 4 and c = -8) unusual combinations of low Z_e and V_m are filtered (*mask_clutter*, see Fig. A1).
In addition to the clutter mask based on the mean Doppler velocity, isolated precipitation events spanning less than two range-gates are excluded to remove false positive detection due to clutter, which cannot be identified by the combination of high mean Doppler velocity and low radar signal (see Fig. 3, *time-step* = 2).

6. ***L208-209:*** *As previous comment about wind-blown rain detected at the surface.*

* The differences of using the surface observed rain flag and the rain flag from the first radar range-gate are discussed in the new Appendix section B3. In a situation of wind blown rain, both rain masks are likely shifted as it is sketched in new added Fig. 3 panel (b) in the manuscript (see also answer to comment #3.)

7. ***L237:*** *Include some discussion of how frequently these limitations occur and the impact they are likely to have on the overall data quality.*

* We have added the following paragraph to the end of section 3.5:

> **L275ff.**:
>
> The limitations identified in this section strongly depend on the input data and atmospheric situation. They can occur at any time. This section is intended to alert potential users of the software of these pitfalls, which may occur to varying degrees on their data set. To be more precise: The issues with "noncontinuous radar signal" and "cloud detection" originate from the facts, that (i) CBH data might be incomplete and (ii) the radar reflectivity might have some gaps if very small cloud droplets are not seen by the radar. The "cloud layer transition" problem is a bit more tangible. It does not occur very often when cloud layers in the atmosphere are clearly separable (as it is the case for the EUREC^{4}A RV *Meteor* dataset). It can become a frequent problem when cloud layers have very large height variations over the course of a measurement period and/or are vertically not well separated.

8. ***L252-253:*** *Could neighbouring columns be included to mitigate this? Allowing a large vertical gap for virga seems to lead to unlikely results at times (e.g. part of the lower cloud being labelled as virga at 3.4 in Fig. 5)*

* We agree, that the allowed vertical gap for virga is a sensitive threshold in the configuration of the Virga-Sniffer. As it is stated in the text, it should be set to zero to avoid False-Positive detection of Virga. Nevertheless, allowance for gaps is virga is required in order to catch fall-steaks advected into the radar volume, as checking neighbouring profiles is not implemented in the Virga-Sniffer. We have strongly considered it though along with moving to aggregation of virga events to be able to characterize connected events. At this stage, this is out of the scope of the Virga-Sniffer, but might as well be an extension in the future. Nevertheless, even allowing an infinitely large gap for virga detection does not add a large amount of false data points. As clouds are detected first, precipitation is limited between the cloud layers. This is shown in the newly added Appendix B2.

9. ***L263:*** *Due to what?*

* This might occur due to low liquid water content and small droplets in clouds which are detected by a LIDAR system but not by the radar system.

10. ***L280:*** *If I understand this correctly the categories on the inner ring are a subset of the outer ring? If so, why do they not align for aerosols?*

* This seems to be an optical illusion. We double-checked all values, they do align.

11. ***Fig. 6:*** *Annotate the larger classes in the inner ring with the percentages*

* Done as suggested.

12. ***L313:*** *What are the horizontal lines on Figure 8?*

* The values of the virga depth calculated by the *Virga-Sniffer* can only assume certain values. This depends on the radar range-gate resolution (here about 30 m). The horizontal lines resulted from the fact that at certain distances the bins of the histogram spanned several possible values of the virga depths. This issue is resolved in the new version of the figures, which were plotted using different bin widths.

13. ***L313:*** *Given the large number of virga reaching 300 m it would be interesting to see any meteorological observations both surface based or radio/dropsondes to look at profiles of humidity and temperature.*

    * This was done, but because the paper is more focused on the technical nature of the virga sniffer, it was not included.

14. ***L325:*** *By eye there appears to be a loose trend along a line from approx. (0, 0.2) to (1, 1.5). Have you looked at any statistics for these data?*

    * No, we did not consider this trend to be significant.

15. ***Fig. 8, 9b:*** *The y-axis scale is irregular, I assume it should be 250 m per label. Add the extra sig fig to make this clearer*

    * This issue is resolved in the new version of the figures.

16. ***Fig. A1:*** *needs colorbar*

    * A colorbar is now added to Fig. A1.

Spelling/Grammar/Typos

- ***L19(x2), 20, 31, 197:*** *Using above/below is ambiguous when talking about the atmosphere, especially in relation to temperature which changes with height. Use greater than, less than etc.*
- ***L112:*** *Define MPI before use*
- ***L154:*** *less -> fewer*
- ***L261:*** *remove the comma*
- ***L334:*** *1.5 m -> 1.5 km*
- ***L357:*** *pixel -> pixels*
- ***L363:*** *"As application", I'm not sure what was intended here*
- ***L403:*** *suses -> uses*
- ***L404:*** *remove comma*
- ***L457:*** *remove paragraph*

Thank you for carefully reading and pointing this out, these remarks have been corrected in the text.

References

Witthuhn, J., Röttenbacher, J., and Kalesse-Los, H.: Virga-Sniffer (v1.0.0), https://doi.org/10.5281/zenodo.7433405, 2022.