Responses to reviewers: Correction of raindrop size distributions measured by Parsivel disdrometers, using a 2D-video-disdrometer as a reference

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November 19, 2014

In this document we provide responses to the reviewer comments for the discussion paper "Correction of raindrop size distributions measured by Parsivel disdrometers, using a 2D-video-disdrometer as a reference", which is under review for Atmospheric Measurement Techniques (AMT) (reference number AMT-2014-232). For each reviewer comment that required a response, we reprint the comment ("Reviewer"), provide a response ("Response") and detail the resulting changes that we made in the manuscript ("Changes").

1 Anonymous reviewer 1

We thank anonymous reviewer 1 for their review.

1. **Reviewer:** *Thurai et al. 2011 and Tokay et al. 2013 showed that OTT Parsivel had shortcomings on both small and large drop sizes. The manufacturer confirmed the shortcomings of the OTT Parsivel and attributed to the inexpensive and inhomogeneous laser device. This is a hardware issue and this reviewer thinks that it can be corrected through software update.*
   Response: It is useful information that a software update may be able to update the Parsivel hardware and correct the shortcomings of the Parsivel for small and large drops; we thank the reviewer for this comment. A software update, however, can only be applied for future measurements, whereas our technique can be applied retrospectively to existing Parsivel datasets.
   Changes: Added the sentence "The correction does not involve changing the instrument and can be applied retrospectively to existing datasets" to the conclusion.

2. **Reviewer:** *The 2DVD underestimates the small drops less than 0.5 mm in diameter. The removal of secondary drops due to splashing and mismatching are one of the key issues of 2DVD data processing.*
   Response: We agree with this point. Our work presents a technique for using the 2DVD as a reference in order to improve Parsivel measurements. As such the results can only be as accurate as the 2DVD results, which we understand may themselves be flawed.
   Changes: We take this as a comment.

3. **Reviewer:** *The authors introduce a new velocity based threshold (equations 12 and 13), which retains most of the small drops that have been traditionally eliminated due to percent velocity criterion. The new velocity thresholds are subjective and do not screen the mismatched or secondary drops. Since 2DVD is used as a reference, this is an important aspect for this study.*
   Response: The traditional percent velocity criterion involves removing drops that have velocities further than a certain proportion of the expected terminal velocity from said expected velocity. The ques-

tion is then what proportion should be used. Previous works have used proportions of 50% (Tokay et al, 2013) or 60% (Jaffrain et al, 2011). To our knowledge, these proportions are subjective, and they do not screen for mismatched of secondary drops. In contrast, our new approach uses prior information from the 2DVD as a basis for the velocity-based thresholds we use to remove measurements of particles that do not have a plausible velocity. Mismatched or secondary drops are indeed an issue for the 2DVD. Nevertheless, we use the 2DVD as our reference instrument and justify this choice through its better matches to independent rain gauges and its high resolution measurements, as explained in the manuscript in Section 4.4.
Changes: We take this as a comment from the reviewer.

4. **Reviewer:** *The authors used Gunn and Kinzer observations as a reference to correct OTT Parsivel fall velocities. This means that the raindrops are assumed to be falling in still air. If that is the case, it might be better to use Gunn and Kinzer observations in calculating size distribution and rain parameters.*
Response: As stated in the manuscript, we use the method of Beard 1976 to calculate expected terminal drop velocities (pg 8533, line 14). This does assume the drops are falling in still air. However, it should be noted that we use very conservative velocity thresholds that are based on observed 2DVD drop counts. These observed drop counts are real data that we expect to include measurements taken in moving air. Thus we expect also that our conservative velocity thresholds only remove extremely unlikely measurements from the Parsivel datasets. On the issue of using Gunn and Kinzer (or Beard) velocities to calculate the volumetric DSD and rain parameters, such a method would force all drops within each Parsivel equivolume diameter class to be given the same fall velocity. This would in turn neglect air motion and the range of diameters and thus fall velocities represented by each class. Our observations from both the 2DVD and Parsivel reenforce the need to allow different velocities per class.
Changes: No changes made.

5. **Reviewer:** *The second generation of OTT Parsivel (Parsivel2) corrected the overestimation of small drops but had a severe underestimation of midsize drops starting at 1.0 mm in diameter. The manufacturer admitted this matter and attributed to a software bug.*
Response: This is useful information and we thank the reviewer for bringing it to our attention. Tokay et al. 2014 (JAOT) found that Parsivel^2 recorded erroneously low fall-speeds for particles around 1 mm equivolume diameter, and reported that the manufacturer recognized this as a software bug.
Changes: Included in the introduction to the Parsivel disdrometers the sentence: "The original Parsivel was by PM Tech Inc. OTT Hydromet purchased the rights to the instrument and redesigned it in 2005; the result was the first generation Parsivel (P1). The second-generation Parsivel^2 was introduced in 2011, and provided improvements over the first-generation model [Tokay et al. (2014)]". In the section regarding comparisons of Parsivel to 2DVD, we have specified that Tokay 2013 and Thurai 2011 used first-generation Parsivel, and Krajewski 2006 used PM Tech. We made two stylistic changes: we have changed from using "Parsivel 2" to using "Parsivel^2", and hyphenated both first-generation and second-generation in the manuscript.

6. **Reviewer:** *Perhaps the most important aspect of this study is the correction of the size distribution. It is done based on hourly observations. What is the minimum number of observations in an hour to be included to the $P(i)$ ratio?*
Response: For a one-hour time step to be included, there is no minimum number of observations required. However, there are other criteria we use: we subset the available 1-hour time steps for each Parsivel station to those that contained no Parsivel warning flags regarding data quality, and in which less than 10% of the timesteps included contained solid precipitation markers (as determined by the Parsivel instrument), and we only compare time steps for which both instruments being compared measured non-zero rain rates (we set the minimum required R to 0.001 for one hour, which corresponds to one thirty second period in which the Parsivel measured greater than 0.01 mm h^{-1}).

Changes: No changes, because these criteria are explained in Section 4.4.

7. **Reviewer:** *Figure 7 shows the P(i) median for 8 different rain rate intervals. Given the fact that OTT Parsivel overestimates rain intensity, why the authors used Parsivel-derived rain rate? The 2DVD rain rate could be a better reference or we are missing a point.*
   Response: While we use the 2DVD as a reference instrument, we want this technique to be applicable to Parsivels that are not precisely collocated with a 2DVD. For example, in the network we present in the manuscript, we have one 2DVD that is collocated with a Parsivel, but we have other Parsivels in the network. We chose to use the Parsivel-derived rain rate because it is the only indicator of rain intensity that is guarenteed to be available wherever a Parsivel is located. This is stated in the manuscript in page 8538, lines 7-9.
   Changes: We have modified the explanation as follows: "Parsivel-derived intensity was used as it is a measurement of the rain intensity that is always available with Parsivel disdrometers, and is independent of our DSD correction. It is hence easily accessible to all potential users".

8. **Reviewer:** *The overestimation of midsize and large drops is one of the key problems of OTT Parsivel. The drops larger than 2.0 -2.5 mm are overestimated by OTT Parsivel. This problem was resolved in OTT Parsivel2.*
   Response: We have mentioned in the manuscript first-generation Parsivel's overestimation of large drops (eg on page 8524, line 21). We agree, however, that more detail was required on the differences between Parsivel first and second generations.
   Changes: See changes made for comment 5.

9. **Reviewer:** *The probability distributions (Figure 11) showed that the corrected fourth and fifth moments did not have a good agreement with 2DVD.*
   Response: The corrected fourth and fifth moments do not have a perfect agreement with the 2DVD, but they are an improvement over the uncorrected moment distributions. This is shown in Figures 11 and 12. In Tables 3 and 7 there are statistics showing that there is an improvement in relative bias and root mean squared error (RMSE) for all moments, at both five-minute and one-hour temporal resolution. Given these results we maintain that the correction is worth applying because it improves the DSD moments, when compared to the 2DVD as a reference instrument.
   Changes: No changes made.

10. **Reviewer:** *The agreement with a gauge did not show a clear improvement even though the authors think so.*
    Response: We respectfully disagree with the assertion that our correction showed no clear improvement in Parsivel to rain gauge agreement. For example, at the Parsivel station that was collocated with the 2DVD, the correction showed an improvement in absolute relative bias of 14.8% for SOP 2013, at five minute resolution. Further, the point of our correction is not only to improve the rain rate estimation but also to improve the accuracy of the DSDs recorded by Parsivel disdrometers. This improvement is demonstrated through comparisons of the DSD moments with 2DVD.
    Changes: No changes made.

11. **Reviewer:** *While this reviewer appreciates the effort on correcting OTT Parsivel, the findings did not convince that the corrected number concentrations provide more accurate size distribution.*
    Response: To test the accuracy of the corrected drop size distributions, we compared DSD moments before and after the correction to those of the 2DVD. There is an improvement shown (see figures 10, 11 and 12, and tables 7 and 11). We believe, however, that this comment speaks to a point that was perhaps not made clearly enough in the original manuscript; that because the 2DVD is taken as the reference instrument, we match only to the 2DVD. Our aim is to produce a method that will help to adjust Parsivel data to a 2DVD, and we do not test the accuracy of the 2DVD drop size distributions.

Changes: Note added to paper conclusion: "It must be noted that because the 2DVD is used as the reference instrument, the adjusted Parsivel drop size distributions will be, at best, as accurate as the measurements obtained by the 2DVD."

12. **Reviewer:** *It is questionable that these corrections can be applied elsewhere.*
Response: In order to show that the corrections can be applied elsewhere, we have applied them to a dataset recorded in Payerne, Switzerland, which represents a different region and climatology. The method is shown to be applicable to this new climatology, suggesting that it is more widely applicable than just to Mediterranean rainfall.
Changes: We have made multiple changes in the paper to include the new results: Section 3.2 describes the dataset and the differences in climatology between the two field sites, and Section 8 describes the results.

13. **Reviewer:** *It should not be applied to OTT Parsivel2 since the firmware is different.*
Response: We present a technique that can be used in any case in which there are Parsivel disdrometers, and a 2DVD that can be used as a reference. The different firmware in the Parsivel^2 means simply that different correction factors would be calculated by the technique than if it was applied to first-generation Parsivel.
Changes: No changes made.

2 Reviewer 2: F. J. Tapiador

We thank F. J. Tapiador for his positive review, in which he recommended publication as is. Here we respond to three minor comments.

1. **Reviewer:** *'recalibrate' (better than the term 'correct')*
Response: To us, the word 'recalibrate' would indicate a change in the calibration of the instrument, after which further measurements would be more accurate. Our technique is a method for correction of existing data that has been already measured. Since we feel that in the paper we explain what we mean by 'correction' and 'correct', we prefer to leave the term 'correct' unchanged.
Changes: No change.

2. **Reviewer:** *I think the authors are too enthusiastic about their own results ("vastly improved").*
Response: This is a valid criticism about a subjective assessment in the manuscript.
Changes: The word "vastly" has been removed from the abstract.

3. **Reviewer:** *notwithstanding the limitations of the validation exercise (Mediterranean rain)*
Response: It is correct that we had not previously shown the correction applied to a different climatology or region.
Changes: We have now included another dataset from Payerne in Switzerland. See the response to reviewer 1, comment 12.

3 Anonymous reviewer 3

We thank anonymous reviewer 3 for their thorough and detailed review, in which they recommend publication after minor changes. We respond to their comments below.

1. **Reviewer:** *The paper is clearly written and well organized, although I would suggest that adding a paragraph on why the two step approach presented in sections 5.1 and 5.2 were chosen, in order to provide more clarification.*
   Response: We thank the reviewer for the comment and agree we could provide more information in the named sections. The two-step approach was chosen so that both velocities and diameters are addressed by the correction. To use a one-step approach, in which either velocity or drop diameters were corrected in isolation, would neglect one of the primary measurements made by the Parsivel.
   Changes: The introduction to Section 5 has been modified to better reflect the reasoning behind the two-step approach. Further, we have modified Section 5.1, and added a new figure (Figure 4) to show that the velocity correction shifts velocities to be more closely aligned to the drop velocities recorded by the 2DVD, and thus that the two-step approach is justified.

2. **Reviewer:** *Page 8523, line 26: Add Thurai et al., 2007, J. Atmos. Oc. Tech., to the reference since it is in that reference where the 2DVD-based contoured images of drop shapes are shown.*
   Response: We agree this reference should be included.
   Changes: Thurai et al. 2007 added to citation.

3. **Reviewer:** *Page 8524, lines 26-30: This was found to be the case mostly for R > 20 mm/h, so change sentence to 'Thurai et al. (2011) found that Parsivels record higher mass-weighted mean diameter and rain rate than 2DVD, mostly when the rain rate exceeded 20 mm/h.'*
   Response: This change is indeed required in order to accurately represent the previous work.
   Changes: Sentence changed as suggested.

4. **Reviewer:** *Section 2, second sentence: Authors should note that for drops become oblate spheroids for Deq larger than 1 mm - as they have stated, and the Andsager reference is appropriate here - but for drops larger than ∼ 4 mm Deq, base of the drops get 'flattened' more and more, thus deviating from the oblate-spheroidal shapes, and here the appropriate references are Beard-Chuang 1984 (from theoretical considerations), and Thurai et al. (2007) from 2DVD-based contour measurements.*
   Response: We thank the reviewer for pointing out this detail.
   Changes: We have removed the words "oblate spheroids" and simply stated that "small raindrops are close to spherical, but in drops larger than about 1 mm in diameter, the bottom of the drop flattens out progressively with drop size". We have also cited the references suggested by the reviewer (we believe the reviewer intended to mention Beard and Chuang 1987 so have cited this work).

5. **Reviewer:** *Page 8527, last sentence: Note, other formulas are also good approximations, given in Atlas et al. 1973, and also Brandes et al. 2002. The Gunn-Kinzer (1949) data can also be quoted, for fall velocities at ground level and Foote and Dutoit (1969) for the altitude corrections.*
   Response: While the point here was to give an example of one such formula, we agree that more detail is useful. The difference between ground-level and at-altitude fall velocities is beyond the scope of our paper and details can be found in the supplied references.
   Changes: The sentence in question has been modified to read: "Terminal fall velocities in still air can be calculated from the equivolume diameter; popular formulas include those of Beard (1976), Brandes et al. (2002), and Atlas et al. (1973)."

6. **Reviewer:** *Table A1: 30 to 60 seconds are somewhat significant time differences, so just mention that.*

Response: Although we agree that a 60 s time difference can be significant, the significance of a time difference is dependent on the application. In our case, because we train our technique at one hour resolution, a one minute time difference is not very significant. For this reason we prefer to leave this sentence as simply a statement of the observed differences.
Changes: No changes.

7. **Reviewer:** *Fig. 2: Is the y-axis log 10 N(D) ..? If so, what are the units of N(D)..? It seems to be different from the standard units used, namely, /mm/m^3, so please specify.*
Response: The y-axis in Figure 2 was a logarithmic scale using the natural log. The plot shows a probability density, of which the logarithm has been taken, so the y-axis is unitless.
Changes: For clarity, we have made all logarithmic scales in plots in the manuscript log base 10. The axis label remains unchanged for Figure 2.

8. **Reviewer:** *Page 8533, line 23: What is meant by solid precipitation in this sentence - please specify.*
Response: In this sentence, solid precipitation refers to precipitation marked as 'not-liquid' by the Parsivel disdrometer. This deserves better explanation.
Changes: Included the new sentence: "Note that here, solid precipitation refers to any precipitation that does not fit into the Parsivel instrument's criteria for liquid precipitation, which is based on the velocity and size of the particle [see Loffler-Mang and Joss, 2000]".

9. **Reviewer:** *Section 5, 1st sentence: Can the authors provide/clarify justification why these two particular steps were chosen.*
Response: Please see reviewer 3, comment 1.
Changes: Please see reviewer 3, comment 1.

10. **Reviewer:** *Section 5.1: Any specific reason why the velocity is adjusted rather than the drop equivolume diameter.*
Response: In fact, we do adjust both the velocity and the drop equivolume diameter. The velocity is explicitly changed. The equivolume drop diameter is adjusted through the correction of drop concentrations per diameter class.
Changes: For explanatory changes, please see reviewer 2, comment 1.

11. **Reviewer:** *Page 8439, line 4: 'There is clearly a dependency . . .'*
Response: We thank the reviewer for bringing this error to our attention.
Changes: Replaced "There is clearly an dependency" with "There is clearly a dependency".

12. **Reviewer:** *Page 8540, line 4: 'that it is applied to larger drops'*
Response: We thank the reviewer for bringing this error to our attention.
Changes: Replaced "applied larger drops" with "applied to larger drops".

13. **Reviewer:** *Page 8545, lines 8-9: Change 'We conclude that the correction works to make the Parsivels match the 2DVD . . .' to 'We conclude that our correction procedures result in Parsivel measurements matching better with the 2DVD measurements . . .', or something similar.*
Response: We agree that it is better to indicate that our correction method produces results that are closer to those of the 2DVD.
Changes: The sentence in question has been changed to "We conclude that our correction procedures result in Parsivel measurements that better match those of the 2DVD, which itself underestimates rain rate for low rain rates when compared to a collocated gauge."

14. **Reviewer:** *Page 8546, line 14: 'We compare the rain rates after the correction of Parsivel 2 s to those recorded by'. Remove 's' ?*
Response: This is a typographic error, we thank the reviewer for pointing it out.
Changes: The 's' has been removed.

15. **Reviewer:** *Conclusions, Last sentence: - 'Further work is ongoing to test the transferability of the correction method to other climatologies', The authors should certainly be encouraged to follow up their work as they have suggested.*
Response: We appreciate the encouragement and thank the reviewer.
Changes: We have added an application of the proposed method to data collected in Payerne (see Section 3.2 and Section 8 of the revised paper), which supports the transferability of the method.