The discussion paper by Durbin et al. looks quite attractive. There are several countries in the world with weather networks composed of C- and S- band with possible overlapping. A dual-frequency approach applied to C- and S- band radar collocated measurements can be of interest and the set-up of practically co-located radars used for the study is quite uncommon.

However, the manuscript lacks of and adequate description of the development of the technique and a thorough validation.

There are many examples in the literature of techniques aiming at estimating DSD with assumptions on gamma DSD and its parameters. The one proposed is based on Kdp at the two frequencies and the equivalent reflectivity factor at S-band, supposed to be not affected by attenuation due to precipitation.

Response: Thank you for reviewing our manuscript and improving our study with your suggestions. We'd like to address your comments and revised the manuscript following your suggestions.

Usually, algorithms are first investigated in ideal conditions (i.e. through T-matrix simulated measurements) and then the performance is investigated in the presence of different error sources (i.e. calibration, attenuation, spatial gradient, difference in volume sampling, etc.) and finally validated with real measurement and comparison with real data.

Response: As the reviewer suggested, we did study the possibility of using co-located dual-polarization radars to retrieve the DSD through simulation as the first step. In the simulation, we first calculated the backward/forward scattering amplitude using T-matrix method, and then calculated the reflectivity and specific differential phase fields from S-band and C-band for a given DSD assumption. The simulated results are shown as follows for the gamma model using various values of μ and Λ with N_0=8000.

Figure 1

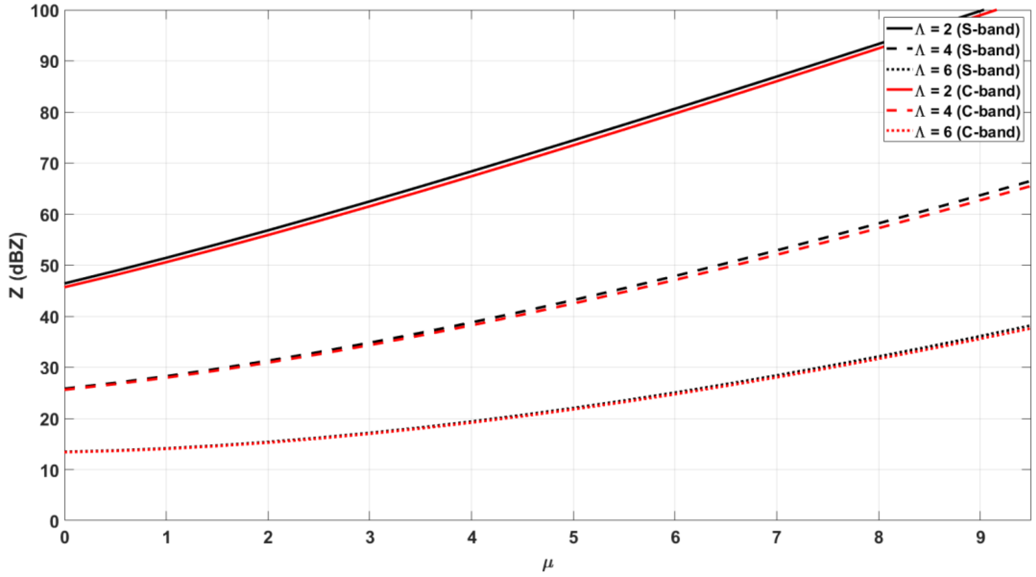

Figure 1 –Simulated Reflectivity For Various Parameters – The S and C-band returns are too similar to provide independent information for retrieval purposes.

Figure 2

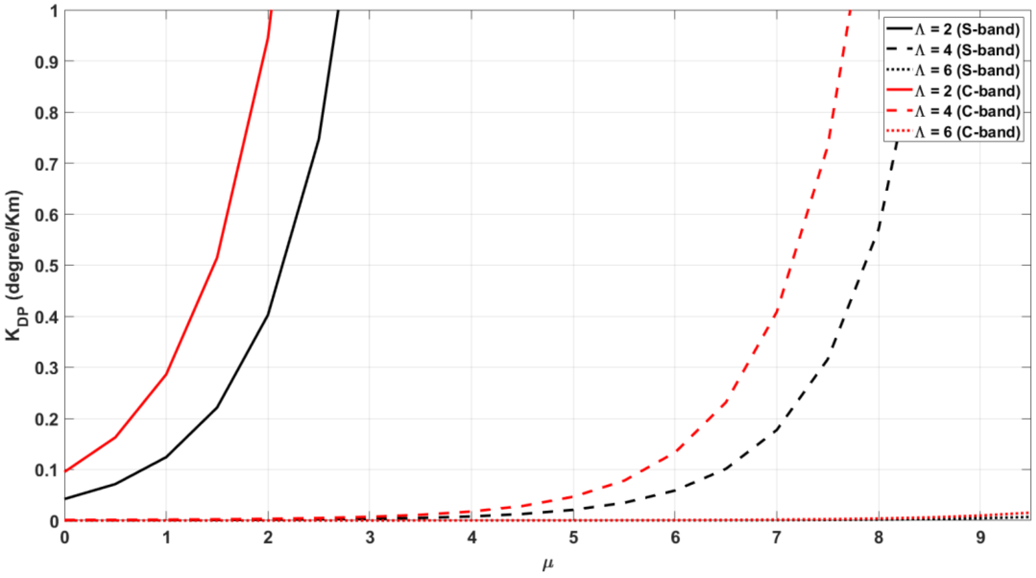

Figure 2 –KDP Variation For Various Parameters – The S and C-band returns vary in KDP values which is a key premise of the algorithm. KDP values separate at the two frequencies at low and moderate values of Λ. The high values of Λ do not provide useful separation as can be imagined by such a quickly collapsing distribution.

Figure 3

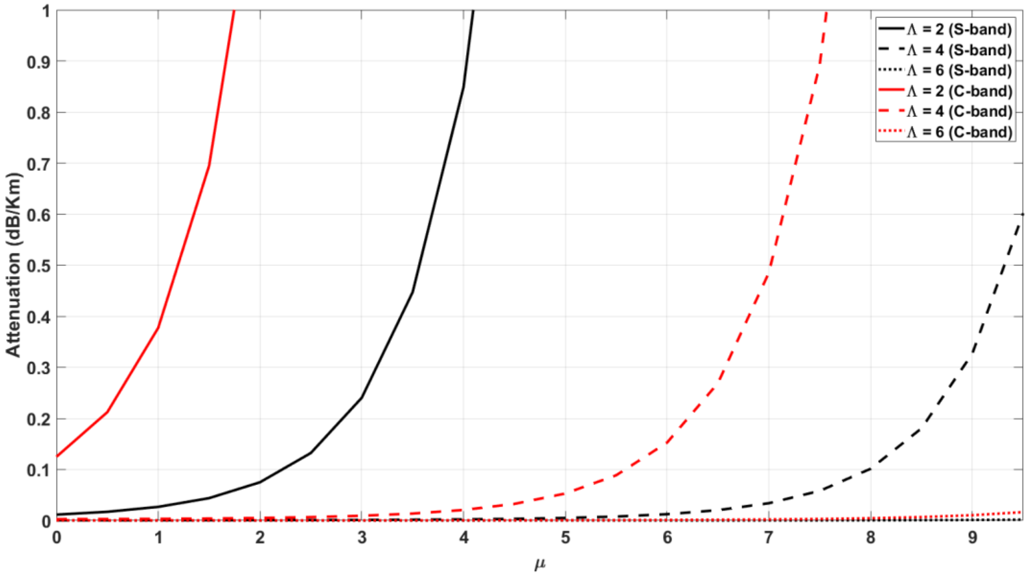

Figure 3 – Attenuation Variation For Various Parameters – As expected, the attenuation is much greater at C-band relative to S-band. Large separation in attenuation values are present for identical gamma parameters.

The simulations reveal a pronounced attenuation in the C-band reflectivity field, whereas the attenuation observed in the S-band reflectivity is significantly less pronounced. Furthermore, a clear separation of KDP values is present at each band. These findings underpin our selection of these specific variables and illustrate the methods through which they can be leveraged for retrieval processes.

Following the reviewer’s suggestion, we will add simulation results into the revised manuscript.

In the first steps of the development missing is a thorough analysis of the impact of the error sources on the retrieval technique.

Response: We appreciate the reviewer's insightful observation regarding the absence of a comprehensive discussion regarding the impact of error sources on our retrieval technique. We acknowledge the oversight and recognize the importance of discussing the sources of error in our manuscript.

The primary sources of error stem from four aspects:

1. Observation Bias: The inherent discrepancy between radar (volume observation) and disdrometer (point observation) can introduce biases. This discrepancy arises because

radars observe a larger volume, whereas disdrometers measure at a specific point, leading to potential inconsistencies between the two measurements.

2. Vertical DSD Variations: Given that radar volumes are situated several hundred meters above the ground, discrepancies in DSDs observed by radar compared to those by disdrometers are anticipated. This issue represents a significant challenge in all radar-based DSD retrieval methods. To mitigate this, our dataset was limited to the two lowest elevation tilts of radar scans, although this approach only partially addresses the error source. This is the extent to which we can control any possible error from this source given the fixed locations of our equipment.
3. Measurement Errors: Errors from both radar and disdrometer measurements were considered. These are discussed in detail in the original manuscript.
4. Retrieval Error: A certain degree of preprocessing is required to remove noise in the data. While this is an essential step, it carries the possibility of smoothing out local phenomena which could introduce error. There is also a potential for error if the retrieval method converges to a local minimum rather than the global minimum, although we utilized an algorithm which is more likely to overcome this possibility.

In response to the reviewer's comments, we will incorporate a detailed discussion of these error sources in the revised manuscript to provide a clearer understanding of their impact on our retrieval technique.

Only a very limited comparison with a Parsivel is shown that could be influenced by many sources of errors, including the limitation of the Parsivel itself (authors honestly use “qualitatively” word). However, even for this case, the error associated with the retrieval is not provided, and the range of variability of retrieved data is not provided as well.

Moreover, the technique is not checked against techniques based on single frequency dual-polarization radar that can be found in the literature so that a reader can understand the advantage of having two radars insted of a cheaper single radar.

The text should be revised, since is not very clear on several parts.

Response: The main omission and criticism you have outlined is consistent with that of the other reviewers- the lack of a comprehensive performance assessment against an acceptable benchmark. This has prompted us to significantly expand the scope of our study.

To address this, we will update the manuscript to explicitly include following revision:

We quantitatively evaluated the performance of the proposed approach and look forward to including the results in the revised manuscript. In the quantitative evaluation, the rainfall rates were firstly estimated using three different approaches: i.) using the retrieved DSD parameters following equation $R = \frac{\pi}{6}\int_0^{D_{max}} D^3 N(D) v(D) dD$ (Bringi 20002, Zhang 2001, etc); ii) using the S-band radar reflectivity (Z) following the WSR-88D R-Z relationship, $Z = 300\ R^{1.4}$ (Ulbrich and Lee 1999) and iii) using the DSD observed by the Parsivel disdrometer following equation $R = \frac{6\ \pi \times 10^4}{\Delta t} \sum_{j=1}^{M} \frac{D_j^3}{S_j^{2DVD}}$ (Raupach and Berne, 2015). The rainfall rates from i and ii were then compared with the iii, which was treated as the ground truth. In the comparison, the relative absolute error (RAE) was calculated as.

$$\epsilon = \frac{|R_d - R|}{R_d}$$

where R_d and R are the rainfall rate from iii and i/ii, respectively.

Total 167 cases were used in the analysis. The criteria of cases selection are:

1.) time difference between S- and C- band scan is within 1 minutes
2.) only the lowest two elevation angle (0.5° and 1.4°) are used.
3.) reflectivity>25
4.) 25<disdrometer range<70 km

The time series plot presented in the following figure illustrates the RAE results for two different approaches. Approach i, our proposed method, is represented by the blue line, while Approach ii, which employs the conventional R(Z) method, is indicated by the red line. The plot demonstrates that estimating rainfall rates using retrieved DSD parameters, as in our proposed approach, yields higher accuracy compared to the traditional Z-R relationship. Specifically, the median RAE for the Z-R approach stands at 0.72, which is notably reduced to 0.53 with our proposed method. This represents a significant improvement of 26.4% as observed in this study.

Figure 4

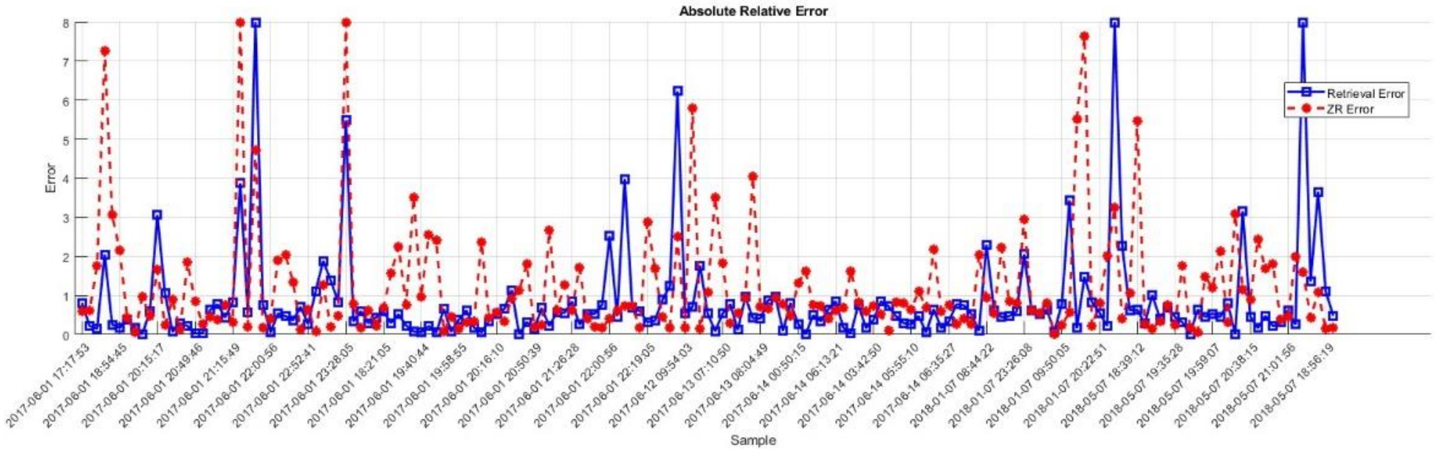

Figure 4 – Retrieval Error Evaluation– The retrieval algorithm’s performance evaluated as RAE is shown in blue while the RAE associated with the Z-R derived rainrate is shown in red. Outliers are truncated at 8 in order to maintain a more useful vertical scale in the plot.

In the revision, the quantitative evaluation results and discussions will be added.

Some specific issues are listed below:

a) A title like “Drop Size Distribution Retrieval using joint dual-polarization radar observation at C- and S- band” could be more suited to the content of the study.

Response: Your suggestion is well taken. Previous dual frequency approaches relied on a much larger separation of frequencies (Ku and Ka bands for GPM for example). Specifying this study is conducted at S and C band is a valuable addition. We will work with the editor to explore the possibility of updating the title.

b) About DSD parametric forms. The Marshall-Palmer is a particular case of a 2-parameter exponential DSD. The exponential was used before the Gamma become successful. It should be noticed that gamma is a model that has its own limitations in describing some natural DSD.

Response: In the revised manuscript, we will include a comprehensive discussion on the limitations of the Gamma distribution. This will cover its challenges in parametrically modeling certain extreme weather conditions and its shortcomings in accurately fitting smaller drop size classes recorded by disdrometers, particularly due to their limited capability in accounting for small drop sizes. Our discussion will aim to provide a clear understanding of these limitations, ensuring that the Gamma distribution's applicability and boundaries in DSD modeling are well articulated.

c) In the introduction, authors are right on the need of assumptions on gamma parameters, although the early technique for Gamma DSD retrieval by Gorgucci et al. 2001 (https://doi.org/10.1175/1520-0469(2002)059%3C2373:EORSDP%3E2.0.CO;2) assumes independent gamma parameters. Also it should be pointed out that the dual frequency techniques described apply to applied to Ku-Ka frequencies for quasi vertical observation while dual polarization radar retrieval operates at quasi horizontal elevation angles based on oblateness of drops which is not seen at vertical incidence.

Response: We acknowledge that our initial assumption may have overestimated the readers' familiarity with the physical distinctions influencing observations across different parameters. While it may be obvious to you and the other reviewers, it may not be readily apparent to a more general audience. To address this, we intend to incorporate a concise explanation in the revised manuscript, closely reflecting the nuances you've highlighted regarding the application of gamma parameters and the operational differences between dual frequency and dual polarization radar techniques. This addition aims to clarify the basis for the observed discrepancies in a manner accessible to all readers.

d) At line 132, authors say that the dataset include light to moderate precipitation. Actually there should be an influence of rain intensity on performance of the retrieval. In fact, in light rain reflectivites at S- and C-band are not so different and Kdp is similar as well apart from the frequency scaling. In this case the contribution of the C-band freqeuncy should be negligible.

Response: We strongly concur with this observation and have accordingly established our data inclusion criteria to require a minimum reflectivity factor of 25 dBZ. We admit this threshold was chosen without conducting a comprehensive analysis to determine the lowest acceptable limit that would ensure discernible separation in KDP values across different bands, rather, we selected a threshold of 25 dBZ as a conservative measure which could be considered an upper limit for light precipitation.

We hypothesize that lower precipitation cases could still show a benefit from including two radars, due to practical considerations rather than any physical rationale. There were many cases we simply had to discard from our dataset simply due to data quality issues. Including inputs at both frequencies would increase the chances of a higher quality input being present for at least one band which the algorithm could use if the data quality standards were relaxed.

e) At line 146, authors say that “This range effect is a predictable issue in radar data processing” What is the meaning of this statement ?

Response: We were referring to attenuation as a function of range. This statement may not even be necessary, however we will update it as follows for clarity.

> *This means that the farther the distance between the radar and the target area, the larger the error in the retrieved DSD. This ~~range~~ attenuation effect is a predictable issue in radar data processing, and it underscores the importance of carefully selecting the range of interest when estimating the DSD.*

f) Fig 4. The bias in reflectivity profile is a calibration error or is due to difference in elevation, time and so on ?

In this specific instance, we attribute the observed bias to the immediate attenuation of the C-band signal by proximate weather conditions, as illustrated in Figure 3 (of the original manuscript). This attenuation begins at the initial points of the radar beam's path. Conversely, in other scenarios, the C-band and S-band signals exhibit congruent returns up until they encounter weather phenomena at more distant gates, where the C-band signal is perturbed to a greater extent due to its susceptibility to attenuation.

We did take steps to mitigate calibration error. Given that the S-band radar (RCWF) is utilized operationally, while the C-band radar (RCMD) is primarily for research purposes, our expectations regarding the calibration of reflectivity measurements have been accordingly adjusted. This calibration challenge is a key factor in our decision to exclude C-band reflectivity from our algorithm. Instead, we have chosen to rely on KDP, which is less affected by attenuation and calibration inaccuracies.

g) Fig 8. This is just visual inspection hampered by the linear scale for N. A meaningful comparison should be done in terms of DSD parameters for a meaningful dataset.

We acknowledge that visual inspection alone is insufficient to validate our methodology. To address this, we have compared the improvements in quantitative precipitation estimation (QPE) accuracy, using our method against Z-R derived rain rates, to fulfill the requirement for a statistical evaluation against recognized benchmarks. Nonetheless, we maintain that the subjective comparison of the retrieved DSDs with disdrometer data contributes valuable insights to our study.

Due to modifications in our methodology, which now restricts the solution space to only allow positive values of μ (previously within the range of $-2 < \mu < 12$), our earlier qualitative plots have become obsolete. The revised example plots, demonstrating gamma distribution parameters for each retrieval, are presented in the subsequent figure. For most cases, employing a linear y-scale has proven to offer a better dynamic range. Therefore, we prefer to maintain consistent scaling across different cases for clarity and comparability

Figure 5

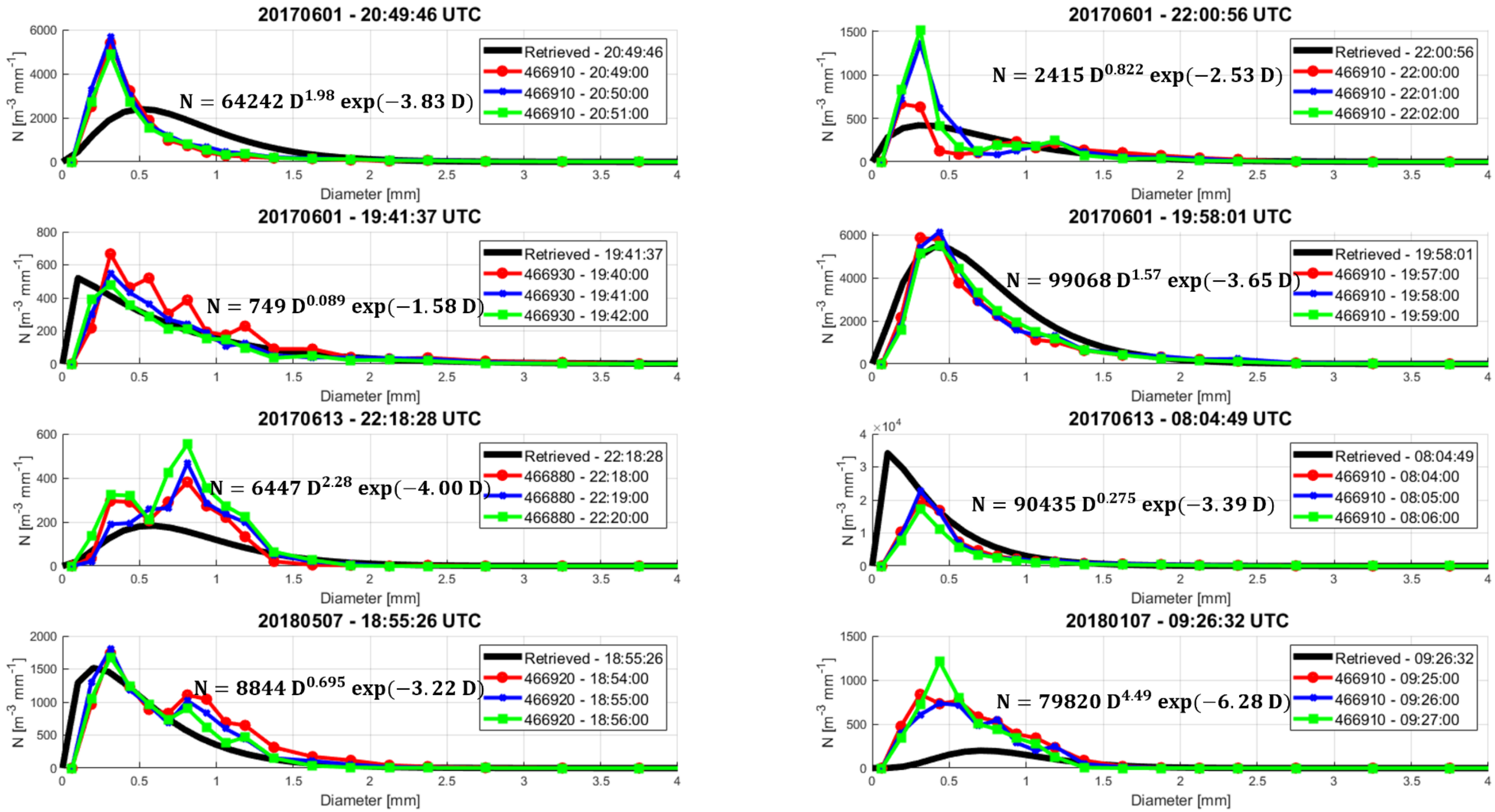

Figure 5 – Updated Example Plots– The disdrometer distribution for the closest time to the radar scan is shown in blue as well as the distributions from the previous minute (red) and next minute (green). The gamma parameters of the retrieved distribution are indicated in the accompanying equation and the distribution itself is represented by the black line of each plot.