Vertical wind estimation with a 94-GHz cloud radar for enhanced DSD estimation using Mie extrema

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In this poster, a retrieval technique for the estimation of vertical air motion in precipitation using a 94-GHz Doppler radar is presented. The retrieval technique is an adapted method that was originally proposed by Kollias et al. (Kollias, P. et al., 2002), which uses the first Mie minimum. This work is to improve the retrieval of drop size distributions (DSDs), by using the estimated vertical velocity as input.

Introduction

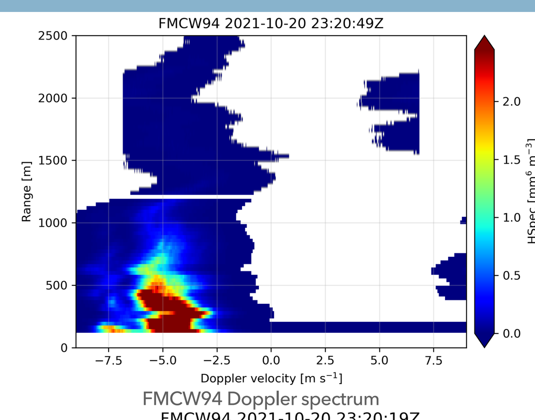
On the right, an example is shown for a Doppler spectrum and a Doppler spectral line for a vertically pointing FMCW94 radar. Three Mie extrema can be recognised. Once the first Mie minimum is located, the vertical velocity can be estimated, by subtracting the terminal fall velocity that is associated with the first Mie minimum. This is the basic principle.

The retrieval technique consists of three steps, which are applied to a Doppler spectral line for each range and each time:

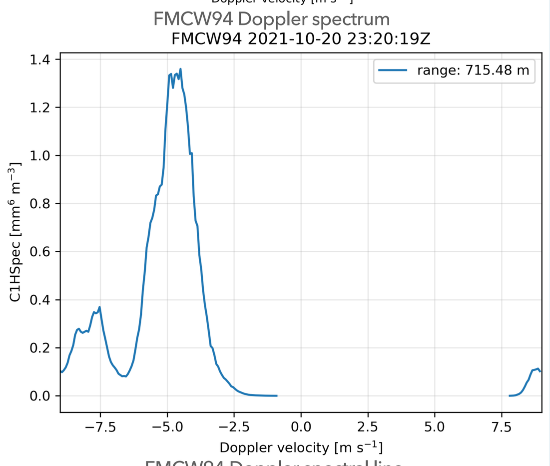
* step A: Identifying extrema,
* step B: Selecting credible Mie extrema and
* step C: Vertical velocity estimation.

Here we address the following challenges:

* What are the limitations and challenges of this technique?
* How can the technique be applied optimally?
* Can the vertical velocity still be estimated, without a valid Mie minimum identification?



FMCW94 Doppler spectrum

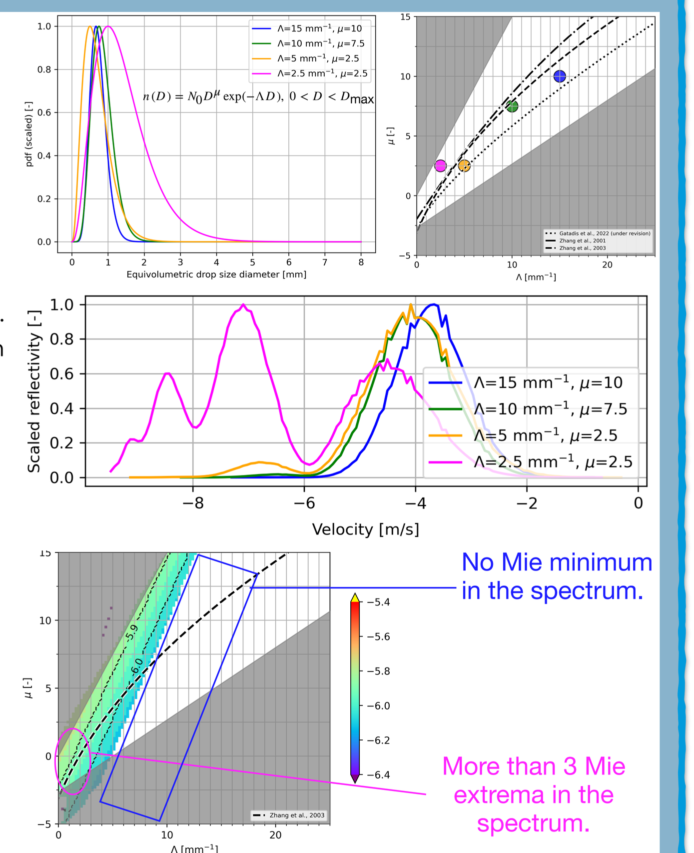


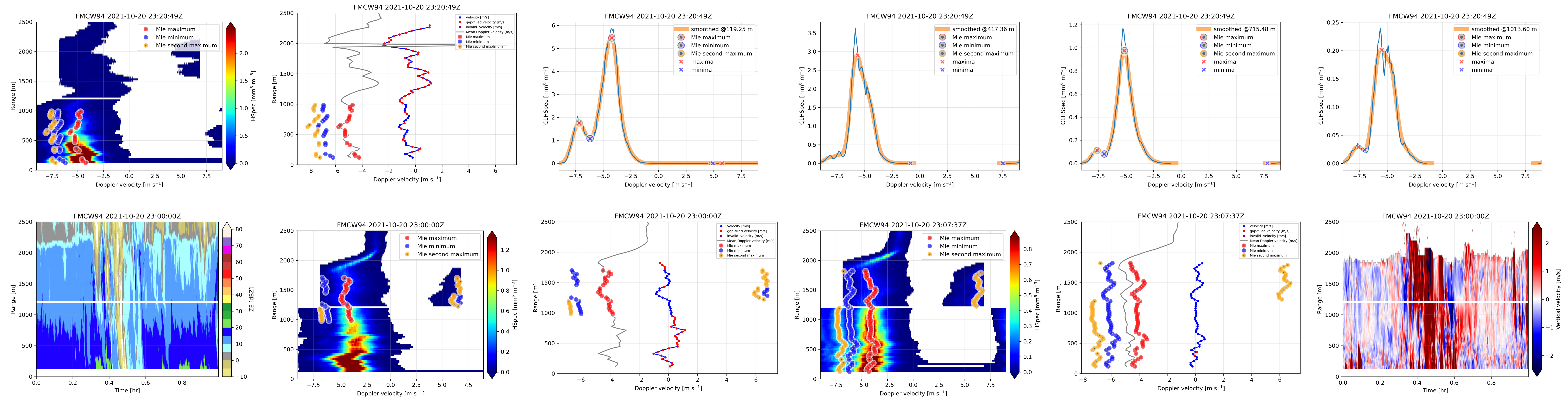
FMCW94 Doppler spectral line.

Simulated Doppler spectral lines

The retrieval technique has been optimised by using theoretical cloud radar spectral lines. The theoretical Doppler spectra have been calculated by using radar cross-sections (Mishchenko, M. I. et al., 1998), terminal fall velocities (Atlas, D. et al., 1973), axis ratios (Beard, K. V. et al., 1987) and a generalised gamma distribution (Ulbrich, C. W., 1983). Typical spectra are shown here, which can be characterised as: "no minimum", "Weak second maximum", "typical", and "multiple extrema".

In the figure on the right, it is shown that the Mie minimum is well retrieved by the retrieval technique for a large portion in the generalised gamma distribution parameter space. It can be seen that for high Λ / small drops the retrieval doesn't work as there is no Mie minimum. The retrieval technique is challenged for low Λ / large drops and more than 3 extrema are present in the spectral line.

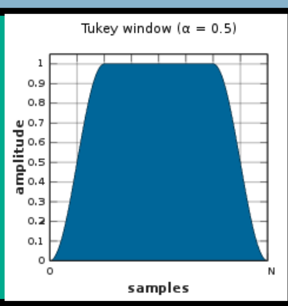




Retrieval technique details

Step A: Find extrema (maxima and maxima)

1. Smooth the spectral line. A Tukey window is used for the averaging with a smooth length of 1.0 m/s.
2. Find extrema (using Python argrelmax, argrelmin, skipping hats).
3. Only one minimum is kept per 5 pixels.
4. Extrema with values close to the noise level are clipped.



Step B: Select credible Mie extrema (using empirical criteria)

1. Select a test maximum $T_{max,1}$. Pick the the largest untested maximum.
2. Search for a test minimum $T_{min,1}$ in the interval [-2.8, -1.0] m/s with respect to the test maximum $T_{max,1}$. Continue, if exactly one minimum is found in this interval. Otherwise, go back to step 1 (and start with another untested maximum).
3. Search for a test maximum $T_{max,0}$ in the interval [+2.0, +3.2] m/s with respect to the test maximum $T_{max,1}$. Continue, if no maximum is found in this interval. Otherwise, go back to step 1. ($T_{max,1}$ and $T_{min,1}$ are considerd as higher order Mie extrema.)
4. Search for a test maximum $T_{max,2}$ in the interval [-0.1, -1.5] m/s with respect to the test minimum $T_{min,1}$. The test maximum $T_{max,2}$ is not required.
5. Calculate the extrema peak/dip widths at 1 dB (1.25). Discard the result for large minimum dip widths for $T_{min,1}$.
6. Save the result.

Step C: vertical velocity estimation

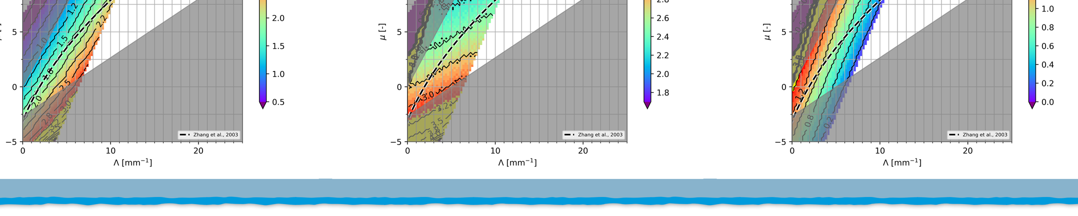
1. Apply an altitude-dependent velocity correction.
(terminal raindrop fall velocity depends on air density)
2. Place the (folded) Doppler velocity in the interval [-vmax, vmax], after the velocity correction.
3. Detect the melting layer. Consequently, discard 100 m below the melting layer.
4. Basic gap-filling is applied as follows:

- A velocity adjustment (vertical velocity minus mean Doppler velocity) is extrapolated. The vertical velocity is calculated by the interpolated/extrapolated adjustment.
- The final results are flagged: 0 = valid, 1 = gap-filling, 2 = invalid.

Discussion

The retrieval technique has been optimised by progressive insight during its development:

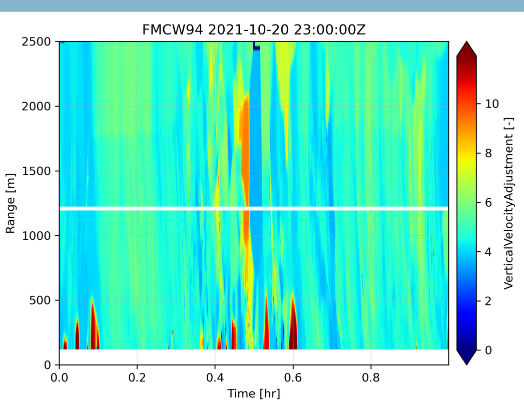
* For finding extrema, smoothing and using the Tukey window is used as an efficient way to damp the raw character of the measurements.
* For the search intervals in steps B.2-B.4, peak intervals have been studied from spectral simulations, which are shown in the images below. Based on that, and the usage of some limited case studies, the search intervals have been determined.
* Step B.4 is there to prevent that a higher set of Mie maximum and Mie minimum is considered as the first Mie maximum and Mie minimum.
* Step B.5 turns out te be helpful to remove invalid results, especially in the case of low signal-to-noise ratio.
* The algorithm is only applied below the melting layer, as it depends on raindrop terminal fall velocity, and raindrop backscattering theory.
* Gap-filling is applied to create a nice consistent end-result for the vertical velocity image. The gap-filled results can be of less quality, and should thus be used with caution.
* The location of the first Mie minimum is (without velocity shifting) expected to be in the interval [5.8, 6.3]. See also the Mie minimum retrieval image in the spectral simulations. Based on that, we can expect an inaccuracy of 0.25 m/s. This inaccuracy may be improved with a rough estimation on the generalised gamma DSD.
* In reality, there is a large variation in the shapes of the spectral lines (see the images in the middle section of the poster).
* The resulting vertical velocity profiles look very consistent in altitude.



Gap-filling of the vertical velocity

For the pixels, where the Mie extrema could not be determined, gap-filling of the vertical velocity is used (step C.4).

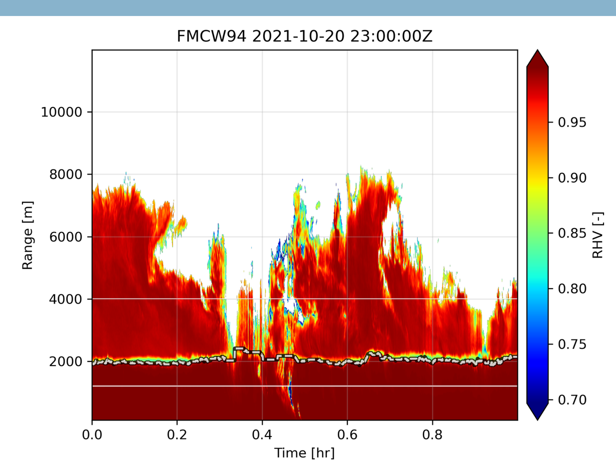
The vertical velocity adjustment is plotted on the right. This variable is interpolated in time and range, from the pixels where the vertical velocity adjustment was estimated. The plot shows that this variable is fairly stable, but has large values in case of positive vertical velocities.



Melting layer detection

A basic melting layer detection has been applied as follows:

1. The copolar correlation coefficient RHV is smoothed in the range direction
2. A mask is created that satisfies:
   - sufficient signal-to-noise ratio.
   - smooth RHV < 0.92
   - ZE > 5 dBZ.
3. The first pixel in the range direction is identified as the melting layer.



4. For times without a result, gap-filling is applied using the nearest-neighbour result.

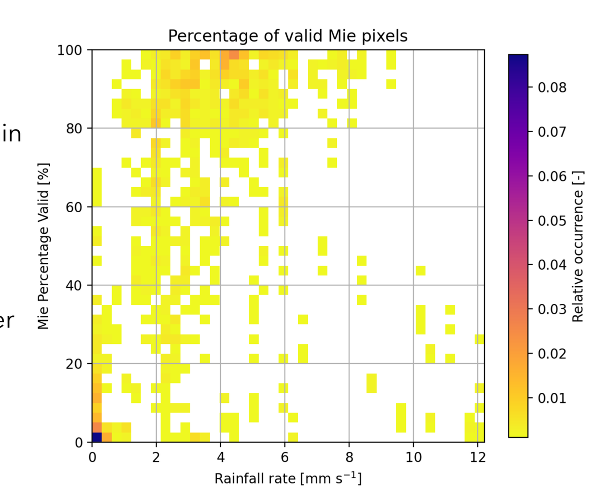
The result is shown in the plot here, and it works nicely. The melting layer height is used in step C.3 of the vertical velocity retrieval technique.

Number of valid Mie pixels

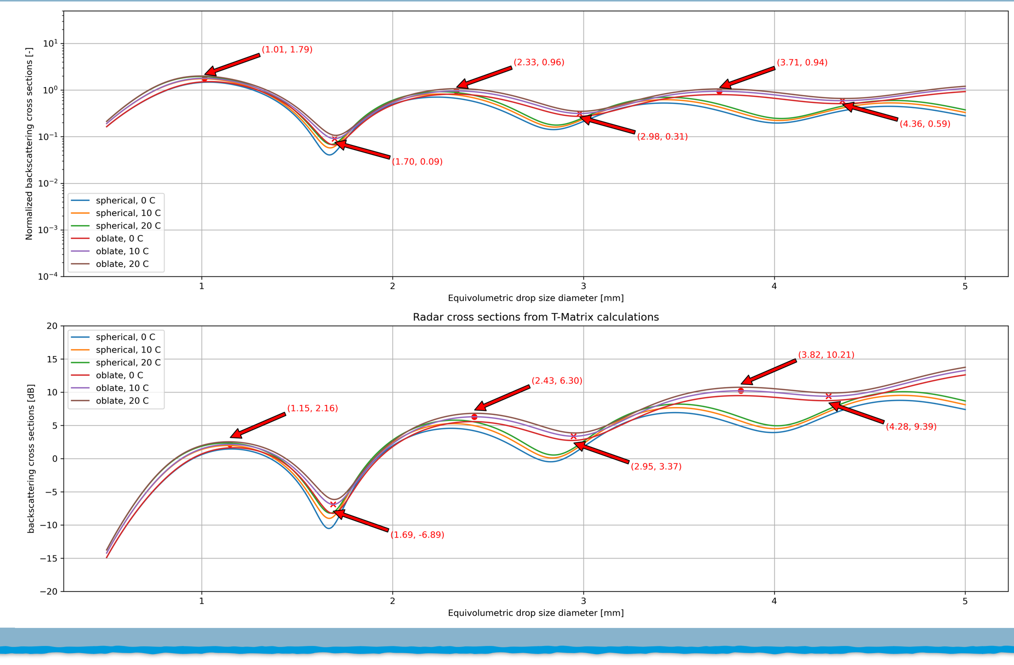
The number of valid Mie pixels is shown on the right. The rainfall rate is coming from a raingauge that is collocated with the cloud radar.

It is shown that often when there is sufficient rain a large portion of the pixels is identified with valid Mie pixels.

Here we note that for this scatter density plot only one hour of data was used, and it can be expected that the scatter plot will become nicer when more samples are acquired.



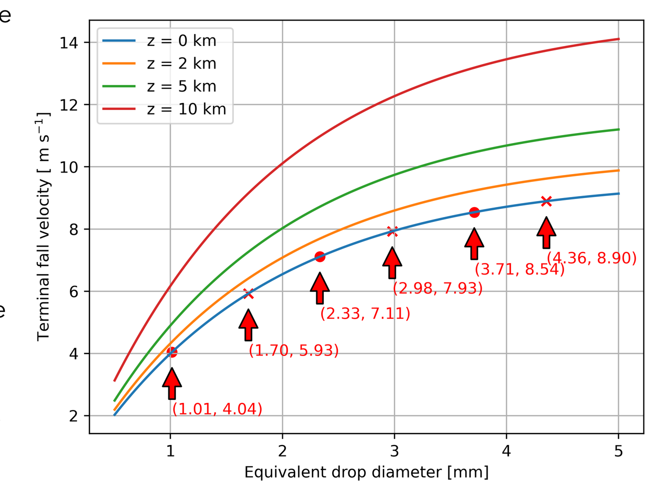
Radar cross sections



Altitude dependency

The raindrop terminal fall velocity is depending on air density. Here we use the $\left(\frac{\rho_0}{\rho}\right)^{0.4}$ -factor from Foote, G. B. et al. (1969) for the height dependence, and a U.S. 1976 standard atmosphere to calculate the air density for a certain altitude.

In the figure it is shown that the altitude-dependence is small, considering that the melting layer is typically at 2 km. This factor may also be used to adjust the search interval values for higher altitudes.



Outlook

Now that it is shown that the vertical velocity retrieval technique is promising, the plan is to further develop this work as follows:

* Create a DSD retrieval technique, that takes the vertical wind velocity as input. It can be expected that a DSD retrieval technique takes benefit of the location of the Mie extrema.
* Validate the resulting retrieved vertical velocities. However, this depends on the availability of data from collocated sensors. We intend to use sonic anemometer data from the Cabauw research site.
* Validate the resulting retrieved DSDs using disdrometer data, and assess the benefit of using the retrieved vertical velocities.

Acknowledgement.

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