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Radar and Lidar Observations of the Melting Process in the Bright Band

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INTRODUCTION

The melting layer of precipitation is known for its high radar reflectivity, and is thus called the bright band. New and unexplained are lidar measurements of the melting layer. This optical instrument receives fewer reflections from the melting layer than from either the ice precipitation above or the rain below. To this phenomenon has been coined the name dark band by Sassen and Chen [1] who published the first clear measurement of this phenomenon. In this article measurements are analysed using lidar together with radar to gain more insight into this dark band. The difference in lidar backscatter between melting layer and its environs is defined as its depth and can amount up to 20 dB compared to the rain (water dark band) and up to 30 dB compared to the ice above (ice dark band).

The radar bright band is usually explained by an increase of the radio refractive index of the melting particle at the top of the melting layer and a decrease of particle size and number density (both due to collapse of the melting particle) at the bottom of the melting layer [2]. Aggregation (in the top) and breakup (bottom) work together to increase the particle size in the middle of the melting layer. This enhances the radar reflectivity of the melting layer. There is still a debate on when this is significant [3], [4].

Explanations for the dark band that are discussed are: crystal imperfections, enhanced backscatter of raindrops for vertically pointing lidar, particle aggregation and breakup, collapse of the particle, and enhanced vertical backscatter of the ice precipitation.

MEASUREMENTS

The measurements come from the CLARA (Clouds and Radiation) database, an extensive multi-sensor field campaign of clouds in the Netherlands held in 1996. As such they were not specifically optimised for studying the melting layer.

During the rain event on the 6th of December 1996 there were multiple cloud layers, Fig. 1. In this case it is clear that the clouds producing the ice precipitation (the lowest one at 1500 m) are well separated from the melting layer (at 800 m). The zero degree level was around 1500 m (!), 700 m above the melting layer, as indicated by a radiosonde released 50 km away from the measurements site at 18 hrs UT. The temperature at the radar maximum (800 m) was 1.6 °C and at the lidar minimum (700 m) 2.5 °C. The humidity was between 85 and 73 %.

In the region with falling crystals between the lowest cloud and the melting layer, the angle of the fall streaks seen by radar and lidar are almost the same. This indicates that the reflections of radar and lidar are dominated by particles with a similar fall speed. It is thus likely that both instruments see more or less the same particles. Note, that the lidar signal in the rain is highest in the first half of the measurement (Fig. 1a) and the radar reflectivity is highest in the second half (Fig. 1b). The radar velocity in the rain increases during the rain event from 2 to 6 m/s (Fig. 1c), indicating that the average rain drop size is increasing. This change in particle size can qualitatively explain the ratio of the lidar and radar reflection as the radar is more sensitive for larger drops compared to the lidar.

The depth of the dark band is around 10 dB for the ice dark band and 4 dB for the water dark band. Note, that the lidar backscatter in the rain is very low for the profiles at the edges of the figure. The dark band computed at the edges is mainly caused by the fluctuating character of the lidar profiles: A calculation of the difference between the maximum and minimum signal in the rain itself yielded similar values at the beginning and ending of this measurement.

Measurements made on the 1st of April 1998 show that the lidar reflections in the rain are very dependent on the pointing-angle, see Fig. 2a. If the lidar is pointed to the zenith the reflections are in the order of 6 to 8 dB times as large as the measurement under a small angle with the zenith (-5°, +5°, +10°). Due to this decrease of lidar power in the rain, the depth of the water dark band is reduced. Both the ice and the water dark band are 5 to 10 dB in the begin of the measurement, up to 8.2 hrs UT.

In the beginning of this measurement a cloud is seen to precipitate ice crystals, which melt a few hundred meters lower, similar to Fig. 1. In the middle of the measurement another cloud unfortunately, obscures the melting layer. Because of this cloud only one change of lidar angle can be used to see if the reflections of the *ice precipitation* also depend on the pointing angle. There seems to be a decrease in reflected power above the melting layer at 8.22 hrs UT, when the lidar is tilted. However, this could just as well be a natural fluctuation.

Another interesting feature of this measurement is that the bright band is much wider than the dark band. The dark band is in de order of 200 meter whereas the bright band is 500 to 800 meter wide, see Fig. 2b. The dark band is in the upper half of the bright band, around 1800 m. The bright band extents between about 2000 and 1500 m.

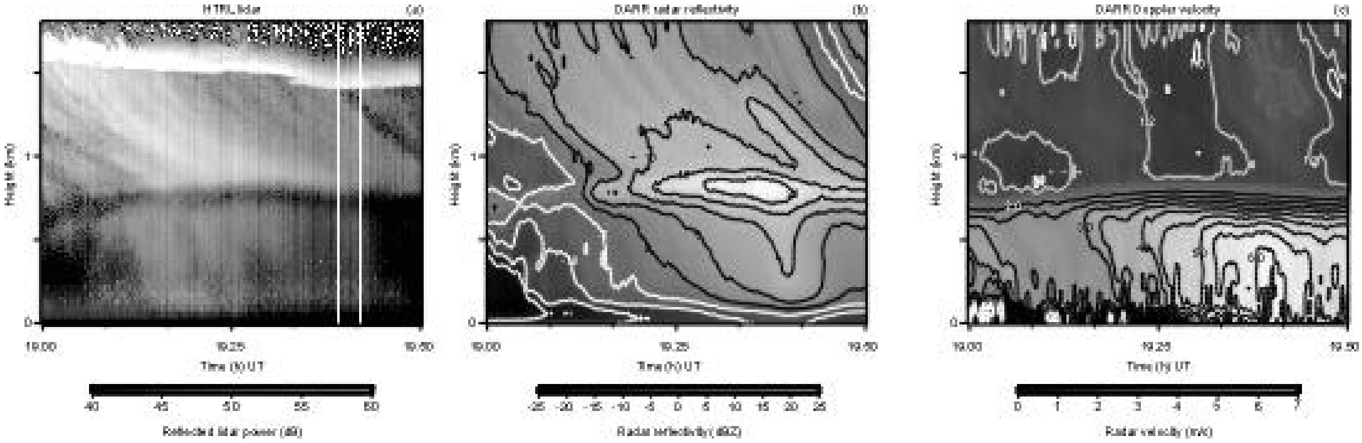

Figure 1. Lidar backscatter (a) and radar reflection (b) of the 6th of December 1996. The melting layer is around 800 m. Fig. 1c shows the radar reflectivity weighted average velocity.

From these measurements and previous ones [1], [5], [6] we infer the following properties of the dark band. A significant number of measurements show a difference in lidar backscatter between the ice precipitation and the melting layer of more than 20 to 30 dB and a difference between the rain and the melting layer of 10 to 20 dB. The dark band is thin. The widest dark band was 200 m to 300 m. This is even the case when the radar bright band is much wider. The dark band can occur during very light rain. The dark band is seen even during rain events with around 0 dBZ.

The decrease in lidar reflection in the top of the melting layer occurs between the start of melting (indicated by an increase in radar reflectivity) and a particle that is half melted; the velocity of a snowflake starts to increase when it is 50 percent melted [7]. This observation has to be used with caution as the lidar return is dominated by relatively small particles compared to the radar reflections. It is thus possible, given a broad particle size distribution, that the lidar return at some height mainly comes from small particles that are already fully melted when the larger particles that dominate the radar return at that height have only melted a little. It would be best if the velocity of the particles dominating the lidar backscatter would be directly measured.

The depth of the dark band seems to be statistically unrelated to the particle number density, which is a sign that interaction between particles may not be important. The measurements with a much larger number density did tend to belong to periods with a less deep dark band, however. The diameter of the particles is statistically related to the depth of the dark band, sometimes positively, sometimes negatively. This is an indication that the size (and the shape which is closely related) of the ice precipitating particles is important.

When the lidar is titled under a small angle the lidar backscatter in the rain is reduced by 6 to 8 dB and the water dark band depth is decreased considerably. This shallow water dark band is typical for a month of titled lidar measurements with an Vaisala CT-25 we looked through. It is possible that the dark band is not present in these tilted measurements due to an insufficient signal to noise ratio in the dark band. This should be checked by repeating these measurements with powerful lidar.

The polarisation measurements of Sassen [6] show a low optical depolarisation ratio in the lower part of the dark band. This is an indication that the particles in the lower half are symmetrical. Most likely the optical backscatter comes from a fully water coated particle, almost completely melted.

HYPOTHESES

In this section some hypotheses are put forward on the causes of the lidar dark band in the melting layer. Many of these ideas depend on assumptions about properties of the ice crystals that are melting. As these properties are not known, these ideas cannot be thoroughly tested yet.

Crystal imperfections

Milk is white because of a large number of small fat droplets. Pure water is transparent. Analogous, the backscatter of an irregular ice crystal can be enhanced by reducing the transparency of the crystal, due to all sorts of imperfections, e.g. rough surface, internal cracks and air bubbles. The melt water can fill up these imperfections and in that way reduce the refractive index gradients that can act as scatter centres. This effect is probably strongest for, e.g., graupel that has many internal surfaces.

Macke [8] made simulation of an irregular shaped particle with air bubbles, to serve as a model for graupel and hail. The backscatter of this particle increased with an increased number of air bubbles. One can imagine that the backscatter of this particle would decrease when the bubbles would become filled with water, which would lower the contrast in refractive index. The opposite is also possible. For specularly reflecting ice crystals the backscatter may be reduced by bubbles and cracks. Macke [8] shows this for a hexagonal column. The bubbles spread the light rays, enhance the side scatter, and thus reduce the backscatter.

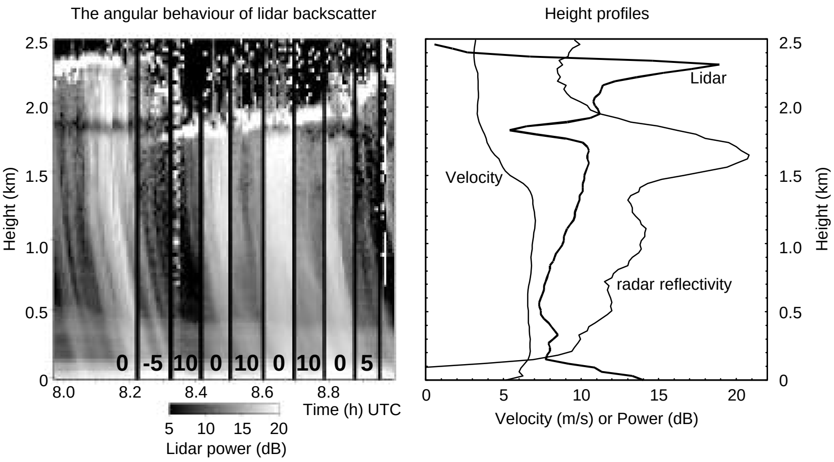

Figure 2. The lidar backscatter (Vaisala CT-75K) in the rain as a function of the pointing angle (2a). The angle in degrees is indicated by the big number at the bottom (zenith = 0). The dark band at 1.8 km and the reflections from the ice crystals above it are obscured in the middle of the measurement by a cloud. Fig. 2b shows the profiles of the lidar backscatter, radar reflectivity (dBZ), and radar velocity (m/s) from the beginning (till 8.2 hrs) of the measurement.

Enhanced vertical backscatter of water drop

The lidar backscatter of rain is much higher if the lidar is pointed vertically than if the lidar is pointed under a small angle. This may be due to the shape of the droplet. The frictional forces on the droplet may flatten the base of the droplet [9]; this would increase the vertical lidar backscatter.

This effect can cause part of the increase of the optical backscatter in the lower part of the dark band, as the water fraction of the melting crystal may experience a similar flattening as the amount of water becomes larger and the velocity increases. If this effect is important for causing the dark band, a positive correlation between the depth of the water dark band and the velocity in the rain would be logical. With increasing size (D < 3 mm), the flatness of the drop increases [9]. However, sometimes a negative correlation is found. A flat drop base due to friction can explain the much smaller water dark band depth in the tilted lidar measurements.

Aggregation and breakup

Aggregation and breakup is thought to be present throughout the melting layer. Aggregation, however, dominates in the top of the melting layer and breakup in the lower half [4]. This results in a larger average particle size and a lower particle number flux in the middle of the melting layer.

If breakup is the dominant mechanism for the water dark band, the lilt angle of the lidar should not matter as was found. The contribution of aggregation and breakup to the high reflections in the bright band is normally thought to be limited to a few dB [10]. The contribution to the dark band should be in the same order of magnitude for a mono-disperse drop size distribution.

The absence of aggregation for very light rain is supported by the study of Fabry and Zawadzki [10]. They conclude that deposition is a more important growth process for the ice precipitation than aggregation for cases in which the rain is below 15 dBZ and they do not expect aggregation to be more important in the top of the melting layer.

Spontaneous (without collisions) breakup of snowflakes is possibility. To explain the dark band by breakup it will have to occur in the lower half of the melting layer. In this part the polarisation measurements of Sassen indicate that the reflections are coming from water drops rather than snowflakes. For water drops spontaneous breakup has only been observed for drops larger than 4.5 mm [9].

Collapse of snowflakes

The decrease in backscatter in the top of the melting layer may be explained by the collapse of a melted snowflake into a much smaller particle. This will reduce the area of the particle and reduce the number density (as the fall speed increases). Both effects will contribute to a lower backscatter. The same effects are used to explain the decrease in *radar* reflectivity in the bottom of the melting layer.

Collapse of the particle is closely related to the particle fall velocity. If the radar velocity is representative, collapse cannot explain the first decrease of the ice dark band and will counteract the water dark band. The radar velocity is of course not identical to the velocity of the particles that dominate the lidar backscatter. The lidar reflections mainly come from the smallest part of the size distribution, this part will also melt first.

Enhanced vertical backscatter in ice

For very light rain it may be more useful to think of single crystals instead of aggregated snowflakes. For crystals the shape and orientation is important. Especially in the optical regime ice crystals can have a very narrow scattering peak around the normal of the particle. Crystals fall with their biggest dimension horizontally aligned, and thus reflect strongly in the vertical direction. This is a well-known phenomenon in Cirrus clouds. Thomas et al. [11] have measured an angular distribution of just 0.3º around the zenith in Cirrus. Sassen [5] has often measured the same angular dependence in virga (precipitation that does not reach the ground). In the upper part of the dark band the power could decrease as the shape changes or because the crystals will no longer be falling horizontally. Asymmetric melting may cause this disalignment or some other cause [6].

With this mechanism a very deep dark band is possible. It may also be able to explain why the dark band begins high in the top of the melting layer. An important problem for this explanation is that horizontally oriented planar crystals have a optical depolarisation near zero and in the dark band measurements of Sassen [5] a linear depolarisation ratio of above 50 percent is found. In the same measurement, 10 minutes before the dark band occurred no specular reflections were seen in the ice precipitation when the lidar was lilted. It would be interesting to see more measurements.

DISCUSSION OF THE HYPOTHESES

The most likely dominating mechanism for explaining the water dark band is the enhanced vertical backscatter due to a flat drop base of a falling raindrop. A secondary effect could be (spontaneous) breakup of the melting particles.

To strengthen this hypothesis measurements with a powerful scanning lidar would be valuable. Such a lidar system should be powerful enough to have a good signal to noise ratio in the minimum of dark band itself and in the rain while measuring under an angle. Scattering calculations would be valuable to estimate how much this mechanism can contribute to the water dark band.

For the ice dark band there are a few good candidates. The most likely are: crystal imperfections that are reduced due to melting, and collapse of the melting particles. Aggregation could play a secondary role.

The role of collapse of the melting particles should be investigated by a near-infrared Doppler lidar. For investigating the importance of crystal imperfections of the ice precipitation measurements in a wind tunnel of natural melting particles should be made. Also a modelling study could provide more insight.

CONCLUSIONS AND RECOMMENDATIONS

The melting layer shows up in radar measurements as a bright band, i.e. a layer with high reflections. In lidar measurements the reflections in a part of the melting layer are low compared to its environs: a dark band. The difference in reflectivity between the melting layer and the rain can be up to 20 dB and compared to the ice precipitation up to 30 dB. Lidar reflections in the upper half of the dark band come from an irregular particle, whereas those in the lower half come from a symmetrical particle. The dark band is quite thin, typically up to 300 m wide. The decrease of lidar reflectivity starts at a height well above the height at which the radar velocity starts to increase. In rain the lidar backscatter is found to be 6 to 8 dB higher when the lidar is pointed to the zenith compared to the backscatter under a small angle.

The explanation for this dark band is far from certain yet. For the water dark band the enhanced vertical backscatter of raindrops is the most likely candidate, and breakup of the melting particles could contribute some. For the ice dark band the best candidates are: crystal imperfections, and collapse. Aggregation may contribute somewhat.

Many uncertainties may be resolved making fall speed measurements of the small particles in the melting layer by Doppler lidars. This could prove whether collapse of the particle is enhancing or reducing the depth of the dark band. More (quasi-)simultaneous measurements with lidars under two observation angles (vertical and some small angle) would provide information about how strong enhanced vertical reflections in the rain are and whether it also occurs in the ice precipitation above the melting layer.

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