The melting layer: The radar bright band is dark for lidar

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Abstract
Measurements of the melting layer were made with radar and lidar, during light rain. At the height at which a weather radar sees a bright band, the backscatter from the lidar has a minimum. Sometimes this minimum is more than 20 dB deep relative to the rain underneath. In this paper the measurements will be analysed in detail. Five mechanisms that can contribute to this effect are discussed:
1. Refractive index change during melting;
2. Aggregation and breakup;
3. Structural collapse of the melting snowflake;
4. Enhanced vertical backscatter of water droplets;
5. The orientation and shape of the melting crystals.

Keywords: radar, cloud radar, lidar, melting layer, orientation of crystals.

1. Introduction
In the Netherlands stratiform rain is mainly produced by the melting of ice particles into rain droplets. Normally this happens in a well-defined layer, just below the zero degree level. This melting layer is characterised by high radar reflections, the so-called bright band.

This bright band is usually explained by an increase of the refractive index of the melting particle at the top of the melting layer and a decrease of particle size and number density at the bottom of the melting layer [1].

The melting layer for lidar is sometimes seen to give low reflections. For this dark band there is not yet a conclusive explanation. In section 4 five possible mechanisms are discussed. First the properties of the dark band will be described in section 3. The instrumentation is described in section 2.

Fig. 1. Radar reflection (a) and Lidar reflection (b) of light rain on 23rd April 1996. The radar shows a bright band in the melting layer at 2.2 km. The lidar receives less reflection from this layer, which is seen as a dark band. Colour versions of all pictures in this article (and some extra) are available on http://irctr.et.tudelft.nl/reports/1998/darkband/
2. Instrumentation

The TU-Delft S-band radar (Darr) has a wavelength of 9 cm and is pointed to the zenith. Darr can detect precipitation or clouds down to -30 dBZ at 2 km. The averaging time of Darr was 5 seconds and the resolution 15 or 30 meter.

Two lidars were collocated with Darr. One commercial system: the Vaisala CT75K (wavelength 906 nm) operated by KNMI with an averaging time of 12 seconds; RIVM operated the other lidar system, which uses a 1064 nm laser and stores single shots every 0.6 seconds [2]. Both lidar systems show the same trend in their observations of the dark band.

The above-mentioned instruments were collocated during the Clara campaigns, a extensive multi-sensor field campaign of clouds in the Netherlands. More information on Clara can be found on http://irctr.et.tudelft.nl/projects/clara/

3. Observations

A quick overview of the Clara dataset reveals that the optical dark band is not rare; in the Clara dataset (49 days) 7 events with dark bands were found. These are most, though not all, of the cases in which the rain was penetrated by lidar. A measurement of a dark band was previously published by Sassen et al. [3].

In the remainder of this section cases of dark bands are discussed in more detail. First three different dark band cases from the Clara dataset. This section ends with a summary of the results of Sassen.

3.1 Case study 23rd April 1996

The radar reflection for the 23rd April 1996 is shown in figure 1a, the lidar backscatter of the same period in figure 1b. From this time period the height profiles of radar reflection, radar velocity and lidar backscatter were calculated, see figure 2.

Remarkable is that the dark band can be very deep. The median of the difference between the minimum lidar backscatter in the melting layer and the rain was about 7 dB. But this difference was often much bigger: 28 percent of the observations it was more than 10 dB and 11 percent of the cases it was bigger than 20 dB. The difference between the dark band and the cloud is even bigger. But it is hard to extract extra information on the melting process from this as an unknown part of the reflection in the cloud may come from particles that do not fall down.

The radar reflection in the rain varied between 0 and 20 dBZ. A dark band of more than 15 dB deep only occurs when the radar reflection in the rain was less than about 15 dBZ (rain rate about 0.2 mm/h).

The velocity of the rain varied between 2 and 7 m/s. This means the droplets have diameters between 0.5 and 2 mm, [4, p. 420]. From these diameters and the radar reflections the number density can be estimated. This number density is in most cases less than 10 m$^{-3}$. There is almost no correlation between the number density and the depth of the dark band. Only for the few points with number density of more than 100 m$^{-3}$ the dark band tends to be less deep.

3.2 Case study 6th December 1996

Special about the dark band on the 6th of December is that the dark band is caused by falling crystals. The first cloud layer (1.5) km is well above the melting layer (0.75 km).

During the free fall, the angle of the falling streaks (caused by variations in number of particles) seen by radar and lidar are almost the same. This indicates that the reflections of radar and lidar are dominated by particles with the same fall speed. As fall speed is a function of size and shape, both instruments are likely to see about the same particles. The fall speed of the radar was 1.2 m/s, which indicates crystals bigger than 0.1 mm [4, p. 438]. Also the ratio between the radar and lidar backscatter shows that the crystals are much larger than in the cloud layer at 1.5 km.

The number density in the rain was normally less than 10 m$^{-3}$, except for one peak which was approximately 40 m$^{-3}$. At the time of this increase in number density the dark band is less deep.
3.3 Case study 1st April 1998
The measurements made on the 1st of April 1998 are special for two reasons. First of all the dark band is just a 100 m wide whereas the bright band is about 500 m wide, see fig. 3. The dark band starts, as in all examined cases, directly at the onset of melting. The second remarkable fact about this measurement is that the lidar reflections in the rain are very dependent on the pointing-angle. If the lidar is pointed to the zenith, the backscatter is sometimes four times as high as the measurement under a small angle with the zenith, see fig. 3.

3.4 Case study published by Kenneth Sassen
K. Sassen et al. [3] also analysed a dark band measured with cloud radar and lidar. The lidar uses polarisation diversity. Sassen shows a specific 90 second averaged profile of both instruments. The lidar depolarisation is more than 50 % in the cloud. Exactly at the minimum of the dark band it drops to 0 %. In the lower part of the dark band the lidar depolarisation remains about zero. The radar depolarisation peaks at the minimum of the lidar dark band and is still high in the lower part of the dark band. The dark band in this profile is 8 dB deep relative to the rain.

4. Discussion
A large number of dark bands are measured by different systems and in different geographical locations and throughout the seasons. This indicates that the underlying physics should not depend much on details of the electromagnetic scattering by the particles and should be applicable to a large set of different particles, with regard to shape and size. A significant number of measurements show a difference in lidar backscatter of more than 20 dB. So the explaining mechanisms have to be able to give a such a large difference. Furthermore the mechanisms should explain an increase in lidar return at the bottom of the melting layer as well as a decrease at the top of the melting layer, as the case of 6 December shows that this decrease is not always caused by the cloud bottom. The polarisation measurements of Sassen show a low optical depolarisation ratio in the lower part of the dark band, so the optical reflection has to come from a symmetrical particle. Five mechanisms will be discussed: (1) A change in refractive index during melting, (2) aggregation and breakup, (3) collapse of the particle, (4) enhanced vertical backscatter by water droplet shape and (5) the orientation and shape of the melting particles.

4.1 Refractive index
The refractive index of the melting particle changes during melting. In an experiment done by K. Sassen in 1977 [5] the refractive index of an artificial melting ice drop was shown to be lower than that of ice as well as that of a water droplet by a factor 2. This can explain part of the optical dark band effect. As Sassen [3] also states himself, the effect is too small to fully account for the observed dark band.

4.2 Aggregation and breakup
Aggregation of the particles can decrease the total area seen by the lidar, just as breakup can increase the total area. This change in area contributes to a dark band if the aggregation takes place in the upper part of the melting layer and breakup in the lower part. Aggregation and breakup of particles in the melting layer like this have been observed [6]. For both aggregation and breakup a collision between particles is needed. Given the low density in the rain of a few droplets per cubic meter, the collision frequency will be very low for this type of rain. Thus breakup in the lower melting layer will be rare. Significant aggregation or riming in the upper part cannot be excluded with this argument. If aggregation and breakup is a dominant effect, the dark band should be deeper when the number density is higher, as the chance of collision then increases. The opposite effect is even seen in the case studies of 23 April and 6 December. So aggregation and breakup is not a dominant mechanism causing the dark band.

Fig. 3. The dark band at 1.8 km is obscured in the middle of the measurement by a cloud. Remarkable is the reflection in the rain as a function of pointing angle. The angle in degrees is indicated by the big number at the bottom (zenith = 0). The radar bright extended from 1.9 to 1.4 km. This difference in width may be because radar mainly sees the relatively large particles compared to lidar.
4.3 Collapse of snowflakes
The decrease in backscatter in the top of the melting layer may be explained by 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 due to reduced friction). Both effects will contribute to a lower backscatter. The same effects are used to explain the decrease in radar reflection in the bottom of the melting layer. The dark band is seen, however, at the top of the melting layer. The lidar backscatter decreases already sharply when the velocity is still barely increasing. So although it is necessary to take the change of the particle size into account when modelling the total melting layer, it cannot explain the decrease of reflection in the top of the dark band, and will even counteract the backscatter increase at the bottom.

4.4 Enhanced vertical backscatter of water drop
The case study of the 1st of April 1998 shows that 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 a little bit; this would increase the lidar backscatter in the vertical direction. 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. Further research in this area is needed.

4.5 Orientation and shape of the melting particle
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 [7] have measured an angular distribution of just 0.3º around the zenith in Cirrus.

In the upper part of the dark band the power could decrease as the crystals will no longer be falling horizontally. Asymmetric melting can cause this disalignment; melt-water tends to accumulate at a sharp end of a crystal.

In the lower part of the dark band the power will increase again as the water fraction will increase and reflect more and more power. With this mechanism a very deep dark band is possible. Furthermore it can explain why the optical depolarisation is almost zero in the lower dark band. It also explains why the dark band begins directly at the top of the melting layer. Aggregation may broaden the scattering peak and thus reduce the depth of the dark band, as found.

5. Conclusions and recommendations
In the melting layer during very light rain a dark band is seen with lidar. Several mechanisms have been introduced and their respective contributions were qualitatively evaluated. The first two examined mechanisms (refractive index change and aggregation and breakup) will probably just give a minor contribution to the dark band. The third mechanism (collapse) has to be taken into account, but its height dependence does not fit with the measurements. The fourth effect (the shape of the water droplet) can explain (part of) the difference in backscatter between dark band and rain. Taking into account the shape and orientation of a melting crystal, can complete the picture; Though it explains the measurements well, there is no direct evidence for this last mechanism. A laboratory experiment of melting crystals could make the conclusions more firm.

An experiment with a doppler radar and doppler lidar would be helpful. Velocity information can help to be sure both instruments see the same particles and thus strengthen the sensory synergy; These measurements already shown the power of sensory synergy in gaining a better understanding of microphysical processes.

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References