# Lidar and Radar Measurements of the melting layer in the frame of the Convective and Orographically-induced Precipitation Study

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# ABSTRACT

During the Convective and Orographically-induced Precipitation Study (COPS), lidar dark and bright bands were observed by the Univ. of BASILicata Raman lidar system (BASIL) on several IOPs and SOPs (among others, 23 July, 15 August, and 17 August). Dark/bright band signatures appear in the lidar measurements of the particle backscattering. Lidar data are supported by measurements from the University of Hamburg cloud radar MIRA 36 (36 GHz), the University of Hamburg dual-polarization micro rain radars (24.1 GHz) and the University of Manchester Radio UHF clear air wind profiler (1.29 GHz). Results from BASIL and the radars will be illustrated and discussed at the Symposium to support in the comprehension of the microphysical and scattering processes responsible for the appearance of the lidar dark band and radar bright band. Simulations of the lidar dark and bright band based on the application of a concentric/eccentric sphere Lorentz-Mie codes and a melting layer model are also provided.

## 1. INTRODUCTION

Changes in scattering properties of precipitating particles are found to take place during the snowflake-toraindrop transition in the proximity of the freezing level. A maximum in radar reflectivity, known as the radar bright band, is observed in the microwave domain, while a minimum in lidar echoes appears at optical wavelengths, this phenomenon being referred as lidar dark band [1].

The radar bright band has been known and studied for more than three decades and it is presently a well understood phenomenon [2,3]. Radar bright band is dominated by Rayleigh dielectric scattering effects. As snowflakes descend below the freezing level inside the melting layer, their radar reflectivity increases as a result of melting, because the dielectric constant of water exceeds that of ice by a factor of approx. 5 [4]. Lower in the melting layer, snowflakes collapse into raindrops; since rain drops fall faster than snowflakes, their volume concentration is reduced. This reduction in concentration is the primary cause for the decrease of reflectivity observed in the lower part of the melting layer.

On the contrary, the lidar dark band has been poorly investigated and, to date, no systematic and coordinated observations are available. Lidar observations of the lidar dark band have been reported by Sassen and Chen [1], Demoz et al. [5] and Roy and Bissonnette [6]. Model simulations of this phenomenon have been provided by several authors [7,8]. The lidar dark band is believed to be the result of two conflicting microphysical processes: a) the structural collapse of severely melted snowflakes, leading to a decrease of lidar backscattering due to the reduced particles size and concentration and b) the completion of the melting process, leading to a sudden increase of lidar backscattering associated with spherical particle backscattering mechanisms coming into prominence [1]. The radar bright band peak occurs low in the melting region, just above (approx. 200 m) the lidar dark-band minimum. This position is close to where radar Doppler velocity reaches its plateau.

A comprehensive study of the dark and bright band phenomena has been recently published by Sassen et al. [9]. In this paper, authors report measurements performed by a single-wavelength (532 nm) backscatter lidar system and a three-wavelength Doppler radar (0.32-, 0.86-, and 10.6 cm). Unfortunately, lidar and radar depolarization data, which would have provided further information on the state of the melting particles, were not available from the instruments involved. Instead, lidar and radar depolarization measurements were performed during COPS by *BASIL* and *MIRA 36*, respectively.

#### 2. LIDAR AND RADAR SYSTEMS

The measurements illustrated in this paper were performed in the framework of *COPS – Convective and Orographically-induced Precipitation Study* - held in the period 01 June-31 August 2007. The Univ. of BASILicata Raman lidar system (*BASIL*) was deployed throughout the duration of COPS in Supersite R (Achern, Rhine Valley, Lat: 48.64 ° N, Long: 8.06 E, Elev.: 140 m). *BASIL* operated between 25 May and 30 August 2007 and collected more than 500 hours of measurements, distributed over 58 measurement days.

The major feature of *BASIL* is represented by its capability to perform high-resolution and accurate measurements of atmospheric temperature and water vapour, both in daytime and night-time, based on the application of the rotational and vibrational Raman lidar techniques in the UV. Besides temperature and water vapour, *BASIL* is capable to provide measurements of particle backscatter at 355, 532 and 1064 nm, particle extinction coefficient at 355 and 532 nm and particle depolarization at 355 and 532 nm. Lidar systems for precipitation studies need to be shielded from precipitation, which is not the case of *BASIL*. However, a careful operation of the system till the time precipitation reached surface allowed to capture several precipitation episodes involving melting hydrometeors.

During COPS, lidar data were supported by measurements from the University of Hamburg cloud radar MIRA 36 (36 GHz, 0.83 cm, Ka-band), the University of Hamburg dual-polarization micro rain radars (24.1 GHz, 1.24 cm, K-band) and the University of Manchester Radio clear air wind profiler (1.29 GHz, 23.24 cm, UHF band). Additional ancillary information on the state of the atmosphere was provided by radiosondes, launched every three hours during each measurement session, as well as by a sodar and a microwave radiometer. This large "ensemble" of instruments makes the collected dataset unique for the study of precipitating hydrometeors in the melting layer.

## 3. RESULTS

Figure 1 illustrates the time evolution of *BASIL* measurements of the particle backscatter ratio at 1064 nm (not shown) over a period of approx. 1.5 hours from 13:00 UTC to 14:35 UTC on 23 July 2007. The figure reveals the presence of stratiform clouds, with cloud base at 3.4-3.8 km. Around 14:15 UTC melting hydrometeors start precipitating from clouds.

The freezing level, identified through the radiosonde launched at 14:00 UTC, is located at 3.5 km (black arrow in figure). The dark band appears a horizontal line of smaller particle backscatter values at 2.8-2.9 km between 14:15 and 14:35 UTC (red arrow in figure). Lidar measurements were stopped at 14:35 UTC because of the rain reaching surface and entering the telescope, but the lidar dark band presumably continued for approx. 2 hours. Dark band signatures appear also in the lidar measurements of particle backscattering at 355 and 532 and particle extinction at 355 and 532 nm, as well as in particle depolarization measurements (not shown here).



Figure 1. Time evolution of the particle backscatter ratio at 1064 nm from 13:00 UTC to 14:35 UTC on 23 July 2007 as measured by the Raman Lidar system BASIL. Arrows highlight the location of the freezing level and the lidar dark band.

Clear evidence of a bright band is found in radar measurements from both the clear air wind profiler and *MIRA 36*. Figure 2 shows the evolution with time from 00:00 UTC to 24:00 UTC on 23 July 2007 of the radar reflectivity at 1.29 GHz as measured by the University

of Manchester clear air wind profiler. The radar bright band peak (red arrow in figure) occurs in the melting region at ~3.0 km, just above (100-200 m) the lidar dark-band minimum. Vertical lines in the figure identify the period of lidar dark band observation.



Figure 2. Time evolution of radar reflectivity at 1.29 GHz from 00:00 UTC to 24:00 UTC on 23 July 2007 as measured by the clear air wind profiler. Arrows indicate the location of the freezing level and the radar bright band.

Figure 3 shows the time evolution radar reflectivity at 36 GHz from 13:00 UTC to 16:00 UTC on 23 July 2007 as measured by *MIRA 36*. Again, the radar bright band peak appears around 3.0 km (red arrow in figure).



Figure 3. Time evolution of radar reflectivity at 36 GHz from 13:00 UTC to 16:00 UTC on 23 July 2007 as measured by MIRA 36. Arrows indicate the location of the freezing level and the radar bright band.

Although we show the position of the freezing level in all figures, it is to be noticed that precipitation processes can significantly alter the local atmospheric structure, with the temperature gradient in the melting layer varying as a result of evaporative cooling and vertical motion [10].

In addition to enhanced radar reflectivity, increased depolarization and abrupt change in Doppler-derived particle velocities are found in the melting layer. Depolarization is most commonly increased due to the presence of wetted, asymmetric ice shapes. Figure 4 illustrates the time evolution of the linear depolarization ratio at 1.29 GHz from 13:00 UTC to 16:00 UTC on 23 July 2007 as measured by *MIRA 36*. The figure

reveals the presence of enhanced depolarization values in the bright band layer, where linear depolarization ratio values reach -10 dB.



Figure 4. Time evolution of the linear depolarization ratio at 1.29 GHz from 13:00 UTC to 16:00 UTC on 23 July 2007 as measured by MIRA 36.

The left panel in figure 5 shows the vertical profile of temperature as measured by the radiosonde launched at 14:06 UTC, revealing the height of the freezing level at ~ 3.35 km. The second panel shows the vertical profile of radar reflectivity at 36 GHz, 24.1 GHz and 1.29 GHz, revealing the presence of the radar bright band at 2.95-3.0 km, i.e. 350-400 m below the freezing level at a temperature of 3.4 - 3.9 °C. The third panel shows the vertical profile of backscattering coefficient at 1064 nm, revealing the presence of the lidar dark band at 2.85-2.9 m, i.e. 450-500 m below the freezing level at a temperature of 4.4 - 4.9 °C, while the lidar bright band is approx. 200 further down at 2.7-2.75 km. The fourth panel shows the vertical profile of vertical velocity measured at 36 GHz and 1.29 GHz, with values of 2-2.5 m/s high in the melting layer and values of 3.5-4 m/s in the lower portion of the melting layer. Lidar (at 355 nm) and radar depolarization are shown in the right panel of figure 5.



Figure 5. Vertical profile of temperature as measured by the radiosonde launched at 14:06 UTC (left panel); vertical profile of radar reflectivity at 36 GHz, 24.1 GHz and 1.29 GHz (second panel from left); vertical profile of backscattering coefficient at 1064 nm (third panel from left); vertical profile of vertical velocity measured at 36 GHz and 1.29 GHz (fourth panel from left); lidar depolarization at 355 nm (right panel).

Enhanced radar reflectivity, increased radar depolarization and abrupt change in Doppler-derived particle velocities are found in the melting layer. Radar depolarization is most commonly increased due to the presence of wetted, asymmetric ice shapes. Lidar depolarization at 355 nm shows values of 25-30 % high in the melting layer and values of 5-10 % at the heights of the lidar dark and bright bands. These unexpectedly low values of lidar depolarization may imply that precipitating particles are almost spherical or have a more regular shape. Lidar measurements were stopped at 14:35 UTC because of the rain reaching surface and entering the telescope, but the lidar dark band phenomenon presumably continued for approx. 2 hours.

Simulations of the lidar dark and bright band are performed based on the application of a concentric/eccentric sphere Lorentz-Mie codes and a melting layer model. Mie computations based on a concentric/eccentric sphere code, which consider a melting hydrometeors consisting of an ice core surrounded by a water shell [11]. The concentric/eccentric water/ice sphere model may apply to conditions in the initial melting process [9], when melting snowflake actually consists of a myriad of water coatings and irregular drop beads. Figure 6 illustrates volume of the backscattering coefficient at 350 µm, B355, as a function of the melting ratio, i.e. the core/shell radius ratio, rc/rs, as simulated through the application of the concentric sphere code. Simulations in the optical domain (350 nm) for hydrometeors with a radius of 1.5 mm imply particle size parameter in excess of 25000.

The figure reveals the presence of an abrupt increase of  $\beta_{355}$  for melting ratio values  $r_c/r_s$  of 0.6-0.8, which is to be attributed to the major role played in the back-scatter process of severely melted hydrometeors by rays with large impact factors. It is to be pointed out that coalescence and breakup are completely ignored in this model. A melting model [11] was considered to compute the variability of  $r_c/r_s$  as a function of the range below the 0 °C isotherm.



Figure 6. Volume backscattering coefficient at 350 nm vs. melting ratio  $r_c/r_s$ .

Severely melted ice core can move to the top or bottom of the drop (Sassen and Chen, 1995; Pruppacher and Beard, 1970; Rusmussen et al., 1984). So, we also considered a Mie code for large particles with offcentre inclusions, with the ice core at the top or bottom of the water shell (figure 7).



Figure 7: Schematics of off-centre inclusion particles, with the ice core at the top or bottom of the water shell.

In this case results are obtained with a size parameter x=600, which corresponds to a hydrometeor radius of 35  $\mu$ m. A strong enhancement in backscatter coefficient is observed for a melting ratio of 0.55 when the ice core is at top of water shell and for a melting ratio of 0.8 when the ice core is at bottom of water shell, these results being in general agreement with those obtained with the concentric sphere code (figure 8).



Figure 8. Volume backscattering coefficient at 350 nm vs. melting ratio  $r_c/r_s$ , as simulated through the application of the eccentric sphere code.

In a simplified schematic representation, the lidar dark band can be interpreted as associated with the structural collapse of partially melted snowflakes, leading to a decrease of lidar backscattering as a result of the reduced particles size and concentration (approx. 450-500 m below the freezing level), while the lidar bright band can be interpreted as associated with the progression of the melting process, leading to a sudden increase of lidar backscattering when melting ratio is 0.5- 0.8. More results from measurements and simulations will be illustrated and discussed at the Symposium.

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