TARGET SEPARATION AND CLASSIFICATION USING

11.B2 CLOUD RADAR DOPPLER-SPECTRA

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1. Introduction

Cloud radar signals are caused by a number of targets such as cloud droplets, drizzle, rain, ice particles, snow, hail, plankton (Insects and other non meteorological targets), ground clutter, and maybe others. Sometimes signals from different targets coincide in spectra from single range gates but due to their different Doppler velocities they can be separated in many cases. For interpreting the cloud radar data (e.g. to derive cloud boundaries or micro physical parameters) it is essential to know which parts of the signals are caused by which target types.

Many approaches for this classification task, which are currently in use or under development use the synergy of additional sensors but usually only the first three moments of the co-polarized cloud radar Doppler spectra are considered. Using laser ceilometer allows the determination of cloud bases (e.g. Clothiaux et al., 2000) or to classify clouds with and without drizzle by the ratio between radar reflectivity and lidar optical extinction (Krasnov and Russchenberg, 2006). By the combination of radar, lidar and microwave radiometer data supplemented by temperature profiles a sophisticated target catogarization was performed by Hogan and O'Connor., (2006) in order to derive microphysical cloud parameters (Illingworth et al., 2007). A general restriction of current target classifications is that only one class of hydrometeors is assumed to exist in each sample. In this paper we want to show that the Doppler spectra of the cloud radar MIRA36 contain - in addition to global spectral moments - more information as LDR and multi-peak moments which can be exploited for improved target classifications, and we will drop the restriction of only one hydrometeor class per sample.

The algorithms we have developed are based mainly on the cloud radar data itself. In addition to local spectral/polarimetric features also some statistical properties of the data will be included for the classification. As external information only approximate temperature profiles are needed. The algorithms provide separate profiles for the plankton, the rain, and other hydrometeors and, as multi peak detection is performed, it is possible that all profiles contain simultaneous data at the same range gates. This is important, as multi peak spectra are observed frequently in the cloud radar spectra, where the interpretation of global moments calculated from a mixture of peaks may be misleading. It obvious on the other hand that there remain still many target types and constellations, which cannot be distinguished by our algorithms. Therefore, synergetic algorithms which include lidar, radiometer, and model data are still needed for distinguishing between a greater number of different target types which are classified as cloud or hydrometeor signal by our algorithms.

2. Description of the Algorithms

2.1 Overview

The data processing consists of the following steps:

- A specialized signal processor which is hosted on the PCI bus of the radar PC performs all the data processing up to the averaged power spectra, which are saved to the hard disk of the PC. The further processing steps are performed on-line by the PC. For standard settings (averaging time = 10 s, number of spectral points = 256, number of range gates = 2*500 co-anyd cross channel, 4 byte floats) 8 GBytes of spectra data is produced per day.
- The moment estimation is performed by the program “spcs2dmp”. After noise removal significant peaks are searched in each spectrum. The moments of up to 16

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peaks per spectrum are calculated and saved to the “dmp”-files (Dynamic Multi Peak moments). They are the base for all further calculations, whereas the large spectra files could be deleted after this stage.

- The target classification of the multi peak moment data is performed by “mmclx” (multi mode cluster classification). It assigns each peak to a target type and recombines the moments of all peaks which had been assigned to the same target type. For each target type one profile of moments and some additional results as melting layer heights or statistical properties are saved to a file using NetCdf format.

The programs spc2dmp and mmclx are currently implemented by IDL (ITT, formerly RSI). On a 3 GHz x86 CPU these programs are normally fast enough to catch up on-line with the spectra produced by the DSP if the spectral averaging time is larger than 1 s. Typically an average time of 10 s is used so the CPU has a load of only 10 percent. The processing time of some of the employed algorithms depends on the data, and may increase in cases where many multi peaks are present in the spectra. For this reason the spectra are buffered on the hard disk of the PC.

mmclx uses about 50 parameters for making various decisions. Much of the work of developing mmclx consists of adjusting these parameters. It is important to adjust them so that the classification works with data from different weather conditions. spcs2dmp uses only few parameters and their adjustment is not so critical. So there is rarely need for saving the spectra after processing for re-running spcs2dmp.

In the following two sections more detailed descriptions of spcs2dmp and mmclx are given.

2.2 spcs2dmp

The first step of spectrum analysis is the estimation of the noise level. It is done individually for each spectrum (each range gate and each channel) as the noise level in the lowest range gates and in presence of strong signals is increased. The algorithm of Hildebrand and Sekhon (1974) is used in a slightly modified version in order to prevent the tendency to overestimate the noise and to save CPU processing time. In a first step each spectrum is divided in NHSdiv equally spaced pieces. From each piece the average power is calculated. Then Hildebrand-Sekhon is applied to the averaged spectrum (which has only NHSdiv points). The threshold for discriminating points with signal and points with noise has been reduced compared to the Hildebrand-Sekhon algorithm.

In the lowest range gates ground clutter peaks with no Doppler shift and a width which corresponds to the FFT-window are eliminated.

After removing the noise and the clutter spectral regions are identified which may be regarded as separate peaks. For this purpose first the local minima and maxima are searched. Two local maxima are separated by one of the minima lying between them if one of these minima is a large enough canyon between the maxima. There is quite a lot of freedom in this peak separation. Ideally the spectra should be divided to ranges belonging to the different target types. But that is hard to accomplish. For this reason spcs2dms separates the spectra to more peaks than ideally. In doubt it is better to separate a peak (caused by a single type of scatterers) into two pieces, than to leave a double peak (caused by two different target types) together. In the first case the moments of the two peaks can be recombined later, in the second case spectral information is lost and can not be recovered.

The three spectral moments, SNR (signal to noise ratio), VEL (velocity) and RMS (peak width) are saved for each peak.

Additionally, for each peak with a fall velocity of more than 0.7 m/s the Mie corrected dBZ value (SMR) and the liquid water content (LWC) are estimated assuming that the vertical wind velocity is small and the drop diameters can be derived from the fall velocity (Peters et al., 2006).

Furthermore, for each peak the LDR value is calculated from the power of the peak in the co-spectrum and the power which is present in the same spectral range of the cross channel. Note that peaks are not searched in the cross channel.

These 6 quantities saved for each peak (SNR, VEL, RMS, LDR, SMR, LWC) are denoted as moments below.

For each range gate only those moments are saved to the dmp file which has been found in the spectrum. As in many range gates only one or even no peak is present the dmp files of most days are smaller than the standard moment files which contain three moments for each range gate and channel.

2.3 mmclx

2.3.1 General remarks about mmclx

The peak classification is performed mainly by two processing stages implemented in mmclx: In the first stage each peak is classified by its moments including LDR. After this first stage there are peaks which are certainly classified, others which are only heuristically classified, and others which are non-classified. In the second stage the peaks which where not classified certainly are classified by counting the occurrence of classified peaks in the “three-dimensional” neighborhood, i. e. the neighborhood in time, height, and Doppler velocity. Both processing stages will be described in more detail below.

2.3.2 First stage: Individual classification

In the first stage of classification it is important to get some information about the general weather condition. The freezing level or the melting height, which is 50 – 100 m below, is a crucial parameter for the 1st-stage classification. Below the melting level high LDR values are an indicator for plankton. In and above the melting layer large LDR values can not be used as indicator for plankton as they may as well occur in ice clouds or in the melting layer. A melting layer with increased LDR (denoted as bright band) appears only if there is sufficiently strong precipitation falling through the melting layer. With increasing precipitation the bright band extends to a broad height range below the freezing level. Therefore, during rain plankton detection must be disabled at ranges where the bright band is expected. On the other hand, in situations with only thin clouds high LDR values may be regarded as certain indicator for plankton, even in and slightly above the freezing level.

Different approaches have been tested for obtaining a robust estimate of the melting height. At the Lindenberg site either data from the numerical weather forecast model or from the daily four radiosoundings are available for on- or off-line processing, respectively. At Hamburg the freezing level is roughly estimated using the ground temperatures T0 by T = T0 - HeightAGL/143 [K/m]. Unfortunately, small height errors of the estimated melting layer leads to an erroneous classifying the bright band as plankton or vice versa.

Therefore an algorithm has been implemented which detects the melting layer height on based of the LDR and Doppler velocity profiles. This algorithm often fails in the plankton region. To resolve from this problem it is applied only the plankton cleaned data. Unfortunately, for removing plankton the melting layer height is needed. A recursive approach could be used to overcome this problem. Instead mmclx performs the melting layer detection after plankton removal. Only after the melting layer has been found in several successive profiles at matching heights this melting height is used to override the melting height deduced from temperature data. This melting layer height is used for the next hour before the melting layer is determined from temperature data again. This part of mmclx is still under construction and probably a more general approach is required.

In the course of these investigations another property of the plankton depth was found, which is quite helpful for its classification: When no bright band is present, then the melting height estimated from the ground temperature has proven to be an excellent estimate for the top of plankton signals though this estimate of the temperature profile may be quite wrong.

The information needed about the general weather condition is obtained from the so called “global” moments, the three statistical moments from the whole spectrum including all peaks. From this profile of global moments the following weather conditions are deduced (The thresholds given here are the currently used results from adjustments):

- Ground temperature is below 7°C: IsCold
- The power in at least 3 range gates of 30 range gates above the melting layer have more than -20 dBZ: IsRainy
- Less than 8 percent of the range gates above the melting layer have signal to noise ratios which are more than 8 dB above detection threshold: IsSunny
- Else: IsCovered

For each of these weather conditions three sets of parameters for the plankton detection are defined. Separate sets of parameters are defined for the ranges below, in, and above melting level. So for instance the threshold for distinguishing between plankton and hydrometeors is defined 12 times (4 weather conditions x 3 range regions). The boundaries of these ranges are set according to the melting height, the weather condition, and several adjustable parameters. E.g. it has been found that the melting layer is typically 50 – 100 m below the freezing height deduced from radio soundings. A parameter is defined to account for this offset.

The main task of the first stage is flagging each peak according to its moments. Peaks with high LDR (~> -18 dB, below melting layer) may clearly be flagged as plankton. Peaks with low LDR (~< -19 dB) and large fall velocities may be flagged as rain. Other peaks can not be flagged by looking only at their moments: E.g. a single peak with low LDR can only be flagged as "probably hydrometeor" because a single plankton peak may also have a low LDR due to its orientation or its shape. For other peaks there is no detectable signal in the cross spectrum. So instead of LDR only an upper limit for LDR can be determined. If this limit is small enough the peak can be flagged as "probably hydrometeor". If not, no flag can be assigned.

2.3.3 Second stage: Classification by cluster analysis

For the final classification of each candidate

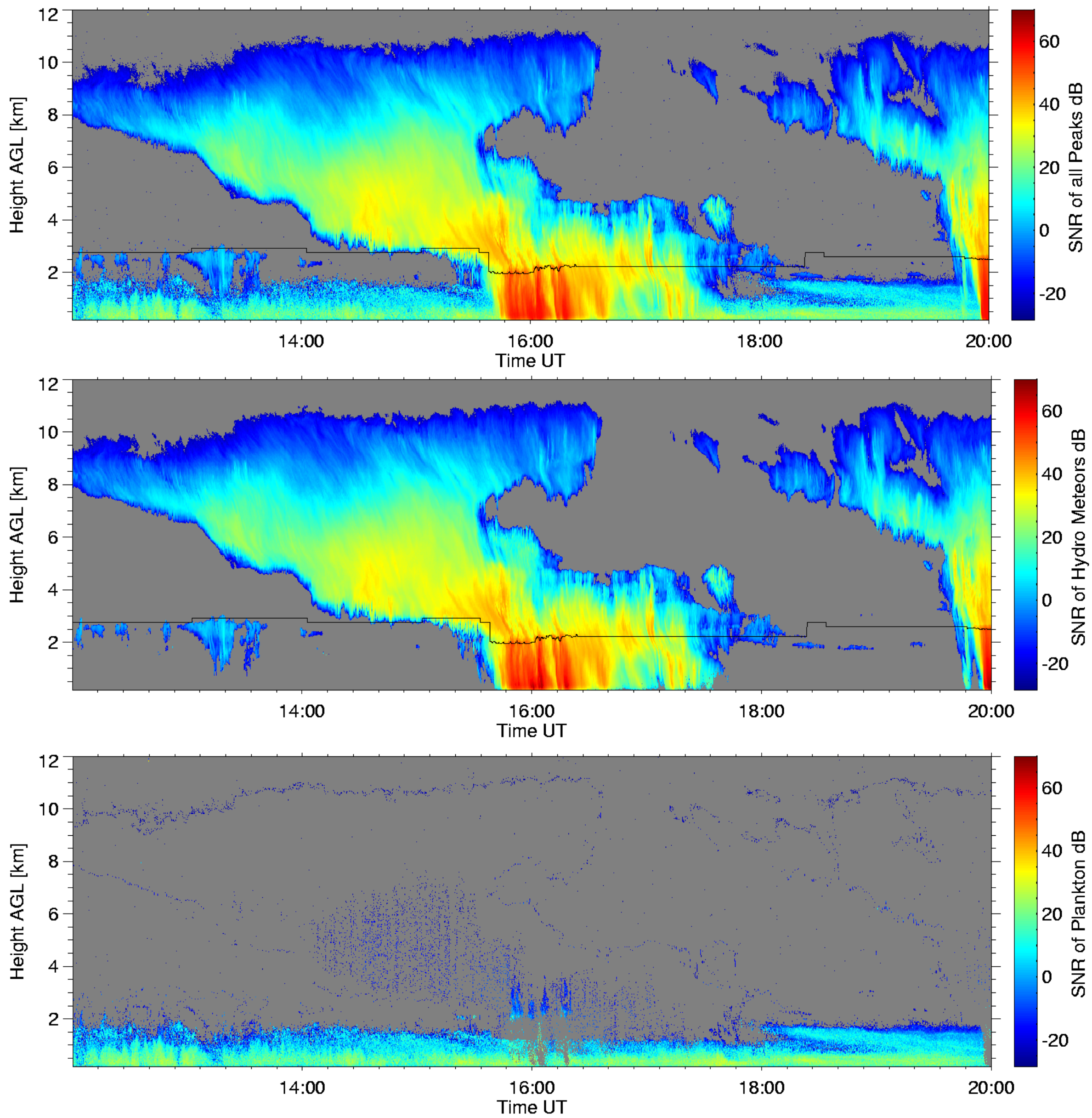

Figure 1: Time-Height cross sections of the signal to noise ratio measured by the MPI-MIRA36 at Hamburg on May 13th 2007. The power (0th moment) in the upper picture is calculated from all peaks, in the middle picture from the peaks classified as hydrometeor, and in the lowest picture from the peaks classified as plankton. The line at about 2.5 km height indicates the melting layer which is deduced from the ground temperatures or from the radar data if the bright band detection is successful (wrinkled pieces, e.g. 15:45 – 16:15). In some regions plankton and hydrometeor data can be detected separately. The small clouds between 12:00 and 14:00 are separated perfectly from the plankton. Above melting layer peaks that are not well clustered are classified as plankton. As side effect the outline of the clouds are flagged as plankton. Also some peeks caused by three path propagation (16:00, 3 km) are flagged as plankton.

peak the peaks in its neighborhood are investigated. Typically 5 dwells of data (in time) and 5 in height are regarded as neighbors. That has the side effect that mmclx delays the output of the classified peaks by 5/2 averaging cycles.

Spcs2dmp provides bebetween 0 to 15 peaks at each point in height and time. Only the one of these up to 15 peaks is regarded as neighbor which is closest to the candidate peak in its Doppler velocity. Note that this is a key choice of this algorithm. It was made for feasibility and it avoids the need for a velocity range defining the neighborhood. Such a velocity range would have to be adjusted

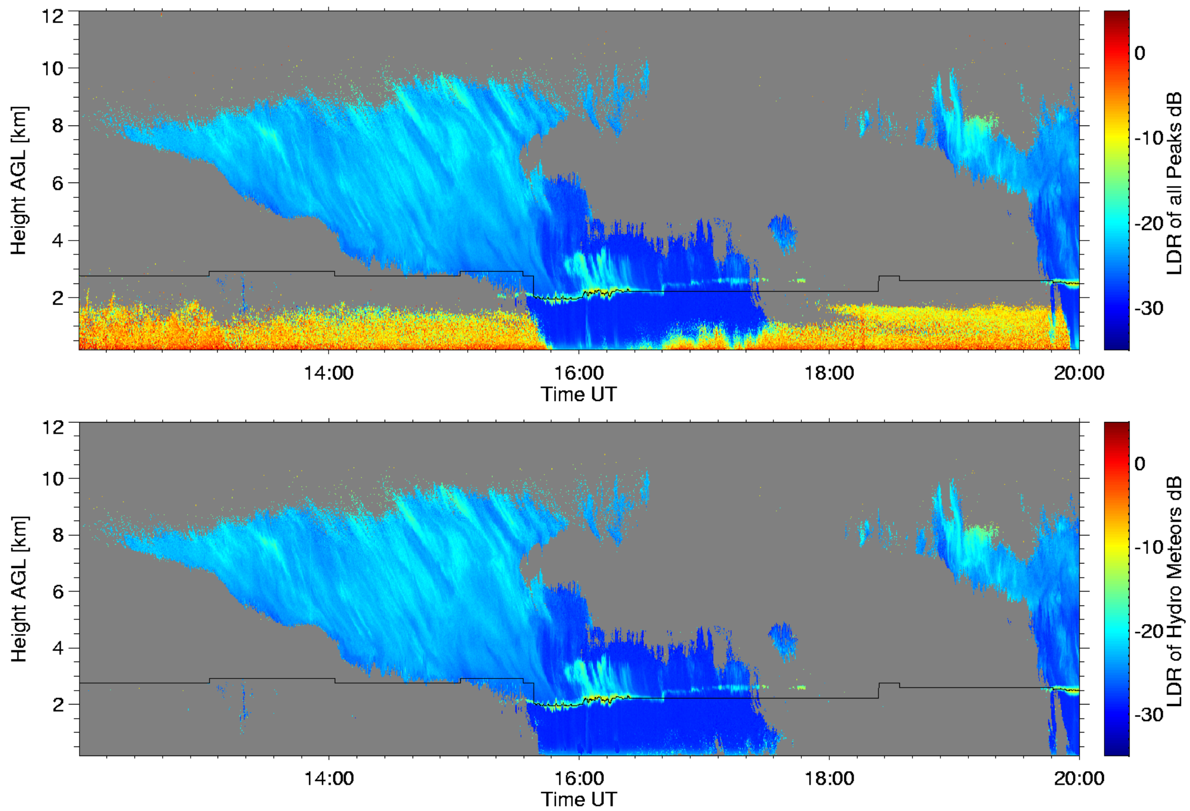

Figure 2: Linear De-polarization Ratio (LDR) from the same measurements as in figure 1 (upper picture: power weighted average of all peaks; hydrometeor peaks).

dynamically according to the turbulence intensity. In this neighborhood the occurrence of each of the flags (nPlankton, nHy, and nRain) is counted.

The final classification of each peak is difficult as various information has to be accounted for. Some of them are more reliable and some of them are only heuristic. The following chain of decisions is made:

- A peak which is flagged as plankton (high LDR below melting layer) may safely be classified as plankton.
- If a peak is flagged as "probably hydrometeor" and there is also a large enough number of peaks marked as hydrometeor in its neighborhood, then it is classified as hydrometeor.
- Peaks that are not yet assigned are classified as plankton if the number of plankton peaks in their neighborhood is large enough or if there is only very small number of peaks in their neighborhood.
- The others are classified as hydrometeors.

Depending on the fall velocity the hydrometeor peaks are split to "cloud" and "rain" peaks. "Rain" here includes all kinds of precipitation that has a significant fall velocity and has grown to a size causing large reflectivities for this reason. In contrast the cloud peaks are caused by a larger number of smaller droplets or ice particles which are optically active and carry the main part of the liquid water content. If the velocity threshold for distinguishing between cloud and rain is chosen as small as -1 m/s then there is a fair agreement between the cloud bases from cloud radar and the ceilometer. Including other criteria for the rain-cloud separation as the peak width (RMS) yet did not improve the agreement between the cloud bases detected by the ceilometer and the cloud radar in presence of precipitation.

2.3.4 Final steps of mmclx

After peak classification the moments of the peaks of each range gate which have been assigned to the same target type are recombined to one set of moments. After this step there is one profile of moments for each target type.

Then the melting layer detection is performed with the velocity and the LDR profile of the hydrometeor data.

Finally the data is saved to using NetCDF format.

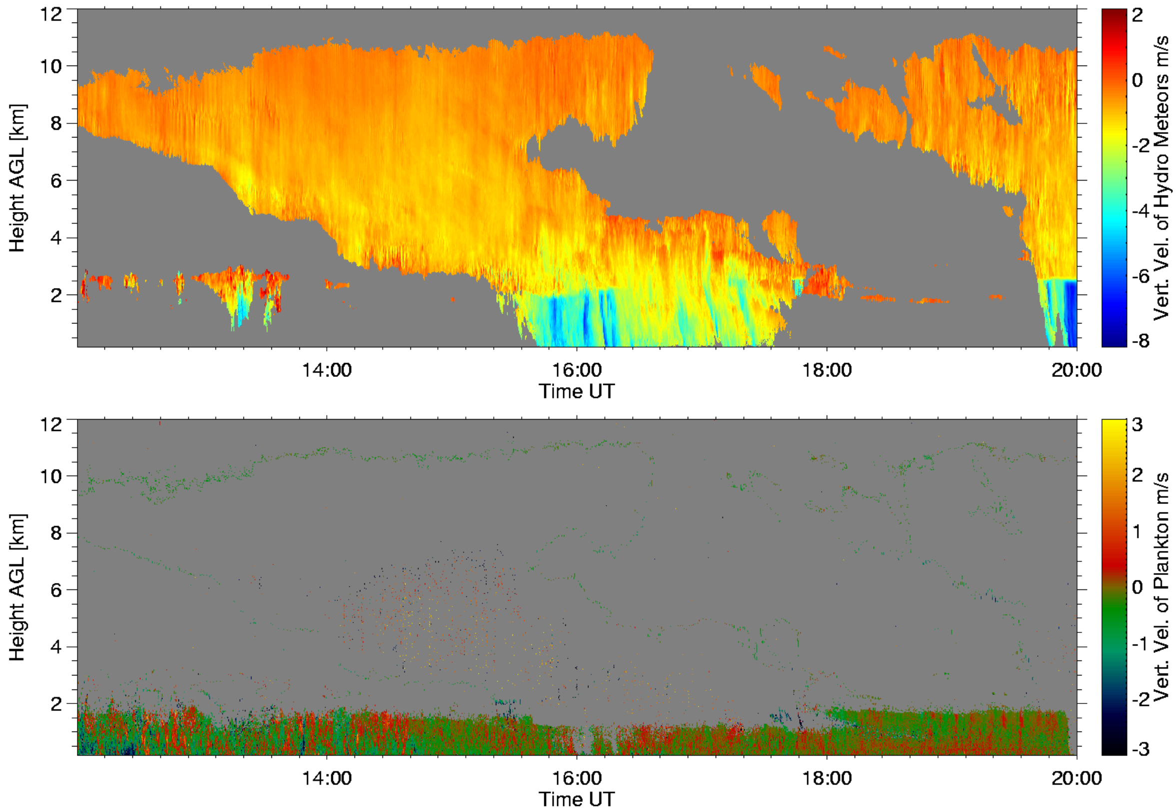

Figure 3: Doppler Velocity of the plankton from the same measurements as in figures 1 and 2. The plankton may be regarded as tracer for the vertical wind turbulence. During strong rain the plankton is covered by by the signal from the rain but it is not washed out. During stronger rain the velocity of the plankton could be obtained from the cross channel.

3. Examples

The new target separation and classification algorithms have been developed with data from the DWD-MIRA36 operated by the German weather service (DWD) at Lindenberg (Görsdorf and Handwerker, 2006), the MPI-MIRA36 operated by the Max-Planck Institute for Meteorology at Hamburg, and the FZK-MIRA36-S operated by the Forschungszentrum Karlsruhe. The first two systems are vertically pointing cloud radars, the third has a scanning unit for azimuth and elevation. As the algorithms are tailored for the vertical mode only in case of the FZK-MIRA36-S they can only be used sporadically when it is operated with vertically pointing beam.

For developing and testing the software spectra data recorded routinely since Feb. 2004 by the DWD each Wednesday between 10:00 and 12:00 UTC, spectra recorded continuously by the MPI in February, July, August, and September 2006, and some spectra recorded by the FZK-MIRA36-S have been used. Since December 2006 the new algorithms are in on-line operation for the DWD and the MPI cloud radars. Once per hour pictures from the unfiltered and from the hydrometeor data are copied to the web server:

http://metekgmbh.dyndns.org.

There the performance of these algorithms can be viewed for a growing amount of data.

The Figures 1 – 3 show a typical example for the separation and classification of hydrometeors and plankton by an 8 hours piece of data from the MPI-MIRA36. In some height-time regions both types of signals are detected at the same time. The classification here is based mainly on the LDR. The general behavior of LDR can be seen in Figure 2. The LDR of plankton is typically above -15 dB and it has a large variations at large wave numbers. The hydrometeor signals below the melting layer have LDRs below -20 dB. Above the melting layer hydrometeor signals may have LDR values of up to -12 dB. Thus, clouds and plankton can not be distinguished by LDR here.

The melting layer is also detected mainly from the LDR values. If the melting layer detection algorithm is applied to the unfiltered data (upper picture in Figure 2) it is obviously often erroneous. Therefore, the melting layer detection has to be applied to the filtered data (lower picture in

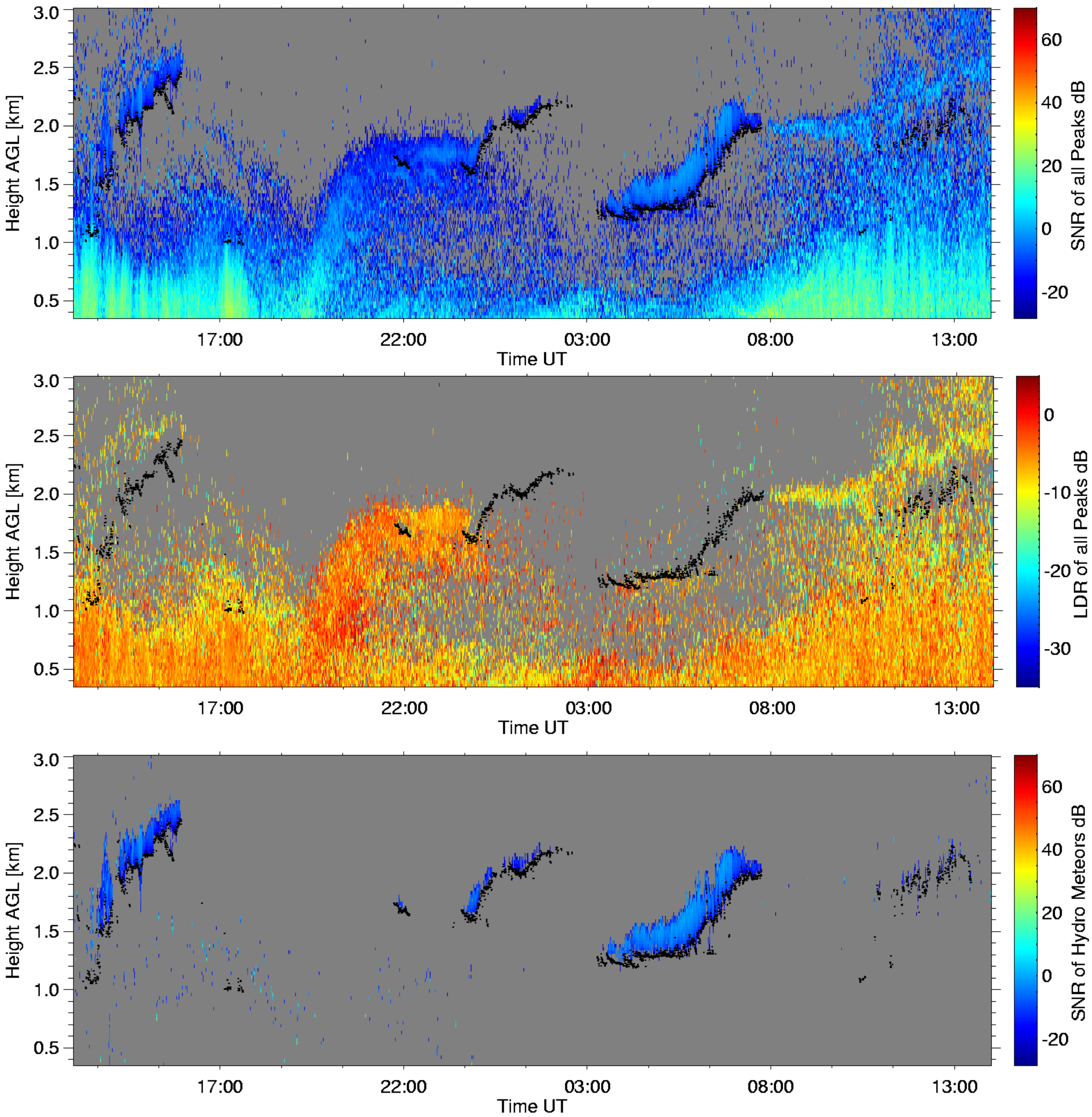

Figure 4: Data measured by the DWD-MIRA36 on 23.05.2007. In the upper picture the SNR of all peaks an in the lowest picture only the hydrometeor peaks are shown. In the upper picture the clouds are hidden in Plankton. Also in the LDR od all peaks (middle picture) its hard to recognize the clouds. The black dots indicate the cloud bases found by a co-located ceilometer. They are in good agreement with the clouds classified by mmclx.

Figure 2). In this example the melting layer detection has worked only between 15:45 and 16:15 (where the black line is wrinkled) though melting layer can be recognized by eyes in a larger interval. Before 15:45, the melting layer height is interpolated from the radiosondes and there it is slightly too high. Some peaks of the melting layer are flagged as plankton as their LDR is as high as the threshold for distinguishing between plankton and hydrometeor peaks. This is a general problem of this method for plankton detection. Especially in spring plankton frequently reaches the melting layer height. There it can not be distinguished from melting snow flakes as both have similar high LDR values. In this critical range plankton can only be filtered according to its statistical properties and is therefore sometimes classified wrongly.

The small clouds between 12:00 and 14:00 are recognized perfectly by mmclx though the signals are too small to detect LDR.

Another example from the DWD-MIRA36 where light clouds are detected which where hidden in the plankton is shown in Figure 4. At the DWD site also a ceilometer is installed, which is very useful to for validating the plankton. If mmclx detects a cloud in the plankton region then the ceilometer should detect the base of this cloud. The cloud bases from the ceilometer are added to Figure 4 as black dots. Unless it is raining good agreement between the ceilometer bases and the clouds detected by the cloud radar and mmclx is achieved. As in the example shown in Figure 4 mmclx is much better in finding clouds inside the plankton than the human expert.

Due to the proportionality of the reflectivity to the 6th power of the particle diameter large particles (e.g. rain drops) are dominating compared to smaller particles. Therfore, optically measured cloud base often does not agree with the radar estimated cloud base. Often (not seen in the shown example) the cloud base detected by the radar is lower than the cloud base detected bey the ceilometer. This may be caused by drizzle falling out of the clouds and drying 100 - 200 m below the cloud base. The drizzle is seen by the cloud radar but not by the ceilometer.

4. Outlook

The plankton detection works rather good. But there are still some ideas for improvements:

- Better melting Layer detection which recognizes horizontal patterns in the LDR time height cross sections.
- Maybe the classification can be improved by searching for clusters in the 4 dimensional space (3 moments + LDR) to which all peaks of the neighborhood are plotted.
- In plankton the variance of LDR is much higher than in hydrometeor signal. This fact may also be useful for the classification.

Some of these suggestions, and maybe others will be investigated by a governmentally founded 2 year research project by METEK and the ZIB in Berlin. This project has been started in May 2006.

The separation of simultaneous cloud and rain peaks is not applicable in conditions with moderate or strong rain because the cloud peak is masked by the much stronger rain peak. Therefore it is still impossible to pinpoint the cloud base under these conditions. In light rain or drizzle on the other hand often double peaks can be recognized. Improved cloud base detection in rain may be achieved by the development of advanced peak detection algorithms. Melchionna (this conference) shows a spectral decomposition procedure into Gaussian curves. In this way multiple peaks can be identified, even if they are coalesced in the observed spectra.

In clouds above the melting layer often double peaks can be observed which have significantly different LDR values. Associating these peaks to ice and and super-cooled water could be very useful for characterizing mixed phase conditions.

5. References

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