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Polarimetric cloud studies at 3.3 GHz

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Abstract. In this paper some polarimetric measurements of clouds done at 3.3 GHz with the Transportable Atmospheric Radar, TARA, are presented. These measurements are done as part of the Cloudnet program. CloudNET is a three-year EU-funded project, which started on 1 April 2001, to use data obtained quasi-continuously at three remote sensing stations for the development and implementation of cloud remote sensing synergy algorithms. Each site is equipped with radar, lidar and a suite of passive instrumentation. The observations will be used in the evaluation of four operational numerical models, and to demonstrate the role that could be played by an operational network of cloud remote sensing stations.

The TARA system is used in the so-called operational mode where the first three moments of measured Doppler spectra are stored. These moments, reflectivity, averaged Doppler speed and Doppler spectral width, are stored every half a second. Polarimetric measurements where done using alternating co- and cross polar antenna settings.

1 Introduction

The transportable atmospheric radar, TARA, designed at the Technical University of Delft in The Netherlands, is operational for nearly two years. The system is constructed in a 12 m standard sized container and is mainly used for cloud and precipitation studies. Being based on the FM-CW principle, TARA is very flexible in its system settings like resolution and sensitivity making it well suited for research applications. Even though, the system is designed to be a research facility, its construction proved to be reliable enough for operational applications. The radar system is located at the remote sensing site of the Dutch Meteorological Institute, KNMI, in the small town Cabauw in the center of The Netherlands. There, it is participating in the European program Cloudnet (Cloudnet). This program foresees in the investigation of using advanced research instruments into operational measurement campaign. The TARA system contributes vertical radar profiles with a temporal resolution of 5 s and a spatial resolution of 30 m to the Cloudnet database.

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2 System description

The TARA system is an FM-CW based atmospheric radar (Heijnen, 1999). Although the antenna pointing can be changed for transportation and measurement purposes, no mechanical scan of the antennae is possible. Two separate antennas are used to isolate the transmitter from receiver. The antennas are parabolic reflector antennas with three feed clusters per antenna. Small feed arrays are position off focus to generate beams at 15° off axis in two orthogonal directions (Moumen). These feeds are single polarized and used in combination with the focal feed to measure three dimensional wind fields (Heijnen, 2001). A minimum of three measurements is needed for wind profiling.

The focal feed is dual polarized. As both antennas are controlled independently, this allows for measuring the full polarimetric scattering matrix. The radar has a single transmitter and a single receiver. Therefore, the polarization scattering matrix can only be measured in a sequence of four measurements.

The radar transmitter is a fully solid state design with a transmit power of 100 W. Due to losses in the antenna excitation circuits, the actual radiated power is 22 W. A low noise receiver with a noise figure of 1 dB is used for highest sensitivity. Using the radar equation for volume scattering, it can be shown that the minimum detectable signal that can be measured at a range of 5 km using a sweep time of 1 ms and a range resolution of 30 m equals to -10 dBz. Doppler spectral processing will give an improvement of the sensitivity depending on the spectral characteristics of the target.

Real-time data processing is done on a dedicated computer system based on seven DSP's and four dedicated FFT chips (Heijnen, 2000). Data is digitized with a 16-bit ADC at a sampling rate of 1 MHz. This system allows for processing

Table 1. Specification of the TARA system

Radar type	FM-CW linear modulation
Central frequency	3.3 GHz
Bandwidth / resolution	2 – 50 MHz / 75 – 3 m
Sweep time	$\geq$ 1 ms
Transmitted power	$\leq$ 100 W, can be lowered in steps of 10 dB
Receiver noise figure	1 dB
Instantaneous dynamic range	$>$ 90 dB
Sensitivity	$-$10dBz (@ $r = 5$ km, $\Delta r = 30$ m, $T_s = 1$ ms)
# resolution cells	512 in range, 512 in Doppler
Doppler resolution	$<$ 8.9 cm/s (@ $T_s = 1$ ms)
Beam width	2.2°
# beams	3
Polarization	H and V, both antennas independent, central beam only
Sidelobes	$-$20 dB first lobes, $-$70 dB in the 90° direction
X-polar limit	$-$29 dB

Fig. 1. The TARA system. Clearly visible are the multiple feed systems to generate off-axis beams.

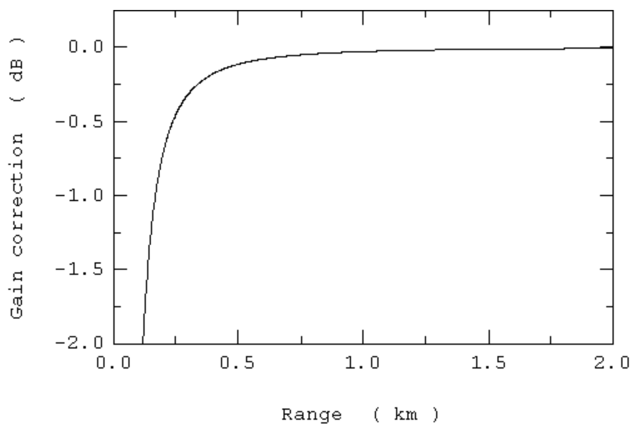

Fig. 2. Correction caused by antenna beam overlap.

of 512 range cells and 512 Doppler cells using a sweep time of 1 ms. Display and storage of the first three moments of the Doppler spectra (reflectivity, Doppler velocity and Doppler spectral width) is done on a PC.

Figure 1 shows the radar system while it still was located at a test site in Delft. The specifications of TARA are given in Table 1.

3 Corrections

The fact that the system uses two antennae means that a range depending correction for antenna beam overlap has to be made (Sekelsky). This correction depends on the antenna beam width and the antenna separation. A good approximation for this correction can be calculated using Gaussian shaped antenna patterns. The TARA antennas have identical antenna patterns with a beam width of 2.2°. The antenna separation is 5.5 m. In this case a gain correction must be applied as shown in Fig. 2. The TARA antennas have a diameter of 3 m. This means that the antenna near field starts at 200 m. For larger distances, the gain correction is less than 0.7 dB. At 500 m the correction becomes less than 0.1 dB. For distances smaller than 200 m, the gain correction is rapidly increasing. However, as this falls within the near field of the antennae, care should be taken in interpretation of these measurements anyway.

In general, antenna patterns are considered to be ideal pencil beams. In reality, this is not the case. The antenna pattern has a finite width, has side-lobes and has a phase characteristic. These antenna characteristics could lead to erroneous Doppler measurements especially in the case of a broad antenna pattern in the presence of horizontal wind. In case of a vertically pointing measurement, a broad antenna pattern will lead to an increase in the measured Doppler spectral width in case horizontal wind is present. The broadening effect will depend on the actual horizontal wind speed but will not influence the measured average fall velocity. In case a lin-

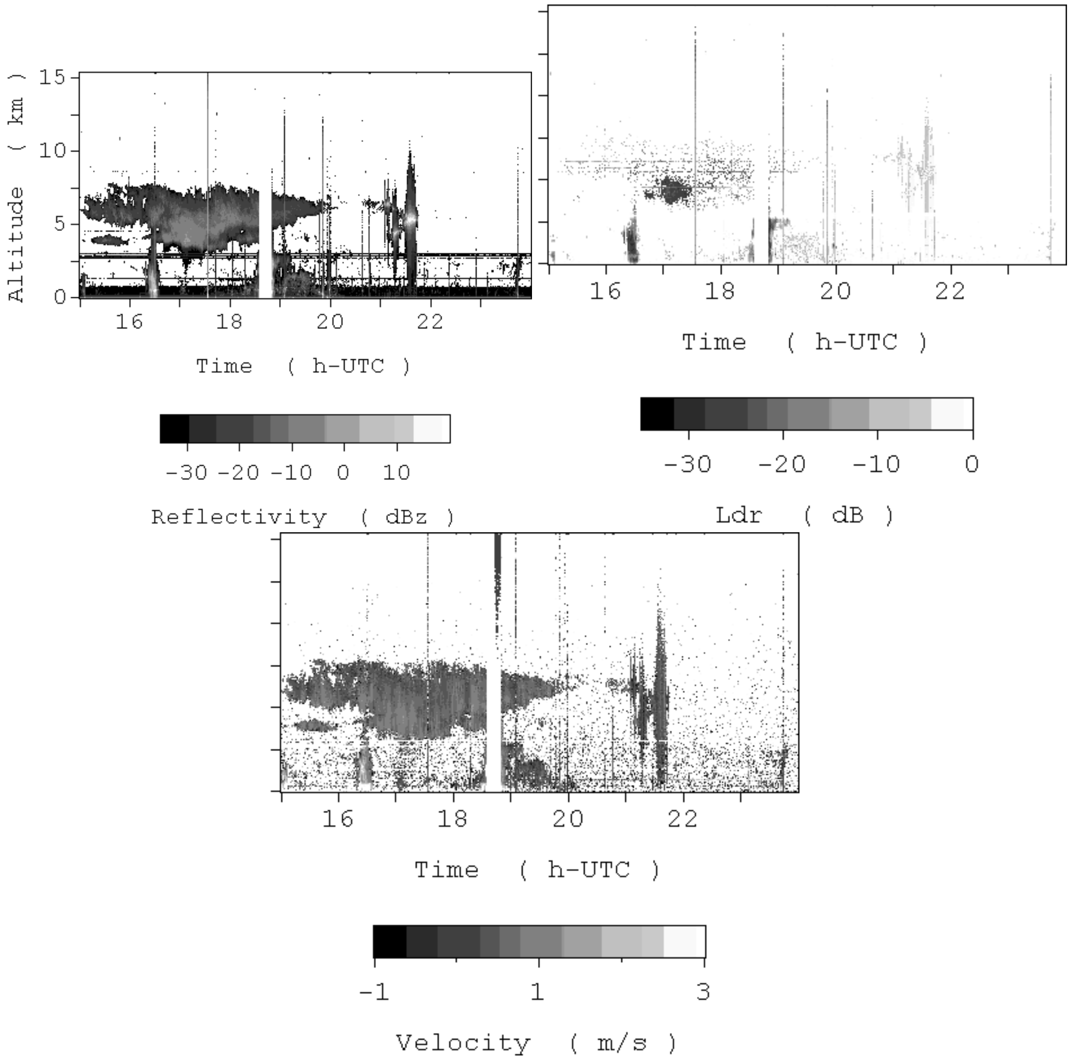

Fig. 3. Polarimetric measurement of a cloud. (a) reflectivity; (b) L_{dr}; (c) fall velocity. The linear depolarization ratio inside the cloud is smaller than -25 dB and in most cases even smaller than -30 dB.

ear phase error exists in the antenna pattern, horizontal wind speed will influence the actual measured fall velocity. In case of the TARA antenna system the phase pattern is symmetric over the main beam and this last effect will not occur.

4 Measurements

In the last year, the TARA system has been used within the framework of the Cloudnet program to build up a two-year database of cloud measurements. The data of several radar and lidar systems located at three different remote sensing stations in the UK, France and the Netherlands will be used to evaluate the cloud representation of four major European weather forecast models. For this, the TARA system has been measuring continuously in a polarimetric set-up. Co-polar and cross-polar measurements have been done alternating switching after every Doppler spectrum. As the sweep time was 1 ms and 512 sweeps are needed for one Doppler spectrum, this means that every half a second the polarization state is changed. The database now covers a period of from October 2001 till July 2002 and is still growing. Data will be available via the Cloudnet project.

An example of a measurement is shown in Fig. 3. This shows a measurement taken on 11 November 2001. It shows the effective reflectivity factor (Z) as well as the linear depolarization ratio (L_{dr}) and the Doppler velocity over a period of nine hours. The measurement was done with a transmit power of 100 W, a sweep time of 1 ms and a spatial resolution of 30 m.

A gap is visible in the data between 18.5 h and 19 h. This is caused by a short rain event saturating the receiver. A similar effect can be seen around 21.30 h. Here, a strong reflection is seen at an altitude of approximately 5 km. In this case, the receiver does not saturate. The reflection is spread out in range due to spectral leakage. Horizontal lines visible in

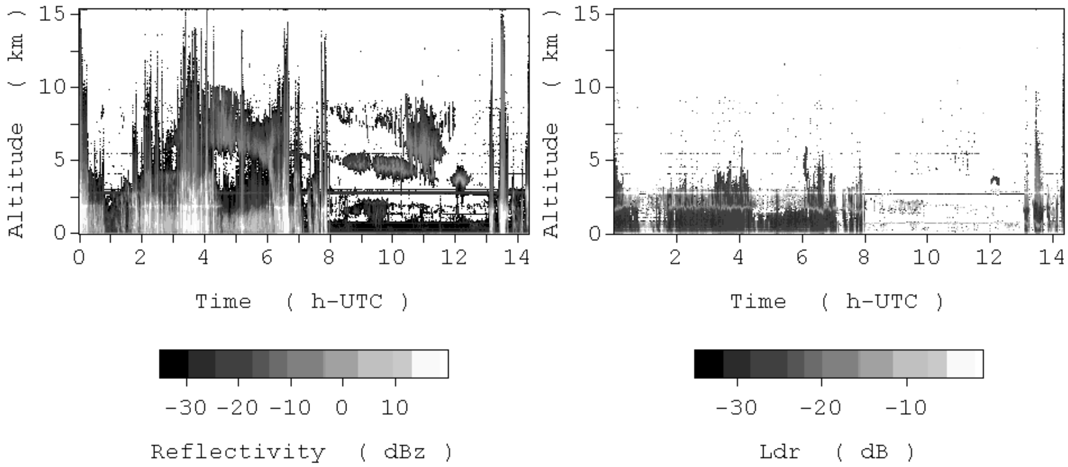

Fig. 4. Measured reflectivity (a) and linear depolarization ratio (b) in case of rain.

the data at e.g. 2.9 km represent system artifacts. A parallax correction as discussed in section 3 has been applied in calculating the reflectivity.

In case of rain, much bigger L_{dr} values are measured as can be seen in Fig. 4. This shows the reflectivity and the L_{dr} during rain while in the same time, a cloud layer is visible above the precipitating layer. In the cloud layer, no L_{dr} can be calculated as the cross-polar reflectivity is below the noise level. In the precipitating layer, L_{dr} values are seen above 25 dB approaching 20 dB. In the melting layer the L_{dr} increases to more than 15 dB on some occasions. The measurement shown in Fig. 4 was done on 22 November 2001. The radar settings where the same as for the measurement shown in Fig. 2, while again parallax correction had been applied.

5 Accuracy aspects

In FMCW radar processing FFT's play an important role. In FMCW systems, the transmitted signal is compared with the delayed received signal using a mixer. The range information is contained in the frequency content of the mixer output signal. To extract this range information, an FFT is used. In case of TARA this is a 1024 samples FFT resulting in 512 range cells. A total of 512 range spectra are collected before a Doppler spectrum is calculated per range resolution cell. Before calculating the first three moments of the Doppler spectra, a number of processing steps are done. First clutter is removed from the signal by suppressing the zero velocity Doppler cell. For stable clutter like buildings this improves the signal to clutter ratio by more than 20 dB. For non-stable clutter, like leaves of trees or grassland, an exponential clutter suppression spectrum is used. Second, filtering is used to reduce spikes from the spectra. Finally, clipping of data is used to reduce noise contributions. This will lower the minimum detectable signal to approximately 40 dBz. From the resulting spectra, the three moments are calculated. When the reflectivity is estimated to be below 40 dBz the value is neglected.

In calculating the FFT's, rectangular windows are used in the TARA processing system. This will result in maximum resolution but has as a drawback high sidelobes in the spectrum resulting in spectral leakage. This will always lead to a reduced resolution but is in general not a big problem. However, when strongly peaked signals are detected, like in case of a melting layer or strong rain, this spectral leakage can lead to saturation effects as can be seen in Fig. 3. In those cases, windowed FFT's will lead to an improvement of the measured data. When the received signals are strong enough to saturate the analogue parts of the radar, data is lost and windowing will not help.

The L_{dr} is calculated by dividing the measured cross-polar reflectivity by the co-polar reflectivity. Both the cross-polar reflectivity and the co-polar reflectivity are calculated as described before. When the cross-polar reflectivity drops below 30 dBz and/or the co-polar reflectivity drops below 35 dBz, no L_{dr} is calculated. This guarantees a high enough signal to noise ratio for the estimate of the L_{dr}. The minimum L_{dr} that can be measured is set by the cross-polar isolation of the antennas. From measurements it was derived that the antennas will limit the detectable L_{dr} to 30 dB.

The measurements described in this paper are done with a sweep time of 1 ms. At a wavelength of 9.1 cm this leads to a Doppler resolution cell of 8.9 cm/s. As the averaged Doppler velocity is calculated from the whole Doppler spectrum, the final accuracy will be higher depending on the width of the Doppler spectrum. The improvement can be up to a factor 10.

6 Conclusions

In this paper some results of polarimetric radar measurements with the Transportable Atmospheric radar TARA are presented. It is clear that for a correct estimate of the reflectivity, parallax corrections are important for ranges less than

500 m. Some accuracy aspects related to the calculation of the spectral moments are discussed. The biggest processing errors will come from the rectangular windows used in calculating FFT's that can lead to a reduced range resolution.

The data presented in this paper as well as other data taken since autumn 2001 will be part of the Cloudnet database. The data will be used for future cloud parameter evaluation of four different weather forecast models within Europe.

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