H.W.J. Russchenberg, V.K.C Venema
A.C.A.P. van Lammeren, A. Feijt
A. Apituley

Cloud measurements with lidar and a 3 GHz radar
Cloud measurements with lidar and a 3 GHz radar
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H.W.J. Russchenberg¹, V.K.C Venema²

A.C.A.P. van Lammeren, A. Feijt³

A. Apituley³

¹ International Research Centre for Telecommunication-Transmission and Radar
IRCTR, Delft University of Technology

² Royal Netherlands Meteorological Institute KNMI

³ National Institute of Public Health and the Environment RIVM

Correspondence:
H.W.J. Russchenberg
Delft University of Technology-IRCTR
P.O. Box 5031, 2600 GA Delft, The Netherlands
Phone: +31 15 2786292
Fax: +31 15 2784046
E-mail: h.w.j.russchenberg@et.tudelft.nl

ESA Technical Officer: B. Arbesser-Rastburg

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Foreword

The work described in this report is part of the Clouds and Radiation project CLARA, in which several Dutch institutes cooperate to study the retrieval of micro and macrophysical cloud parameters. In 1996 three measurement campaigns with a multitude of instruments were organized to measure the cloud structures in The Netherlands. A key element of the experiments was the combined use of radar and lidar to observe different types of clouds. The CLARA-project is, however, not only about radar and lidar. Other instruments were also used during the campaigns. Although the data of these instruments is not used directly in this study, they have been helpful in understanding the events that were analyzed:
- On April 19 and September 4, the National Energy Foundation ECN performed in situ dropsize measurements with an FSSP. This has helped in understanding the actual situation.
- The 20 and 30 GHz radiometer measurements done by Eindhoven University of Technology gave independent information with respect to the cloud of April 18: there was ice in the cloud.

The work described in this report is co-sponsored by the Netherlands Science Foundation NWO, the Netherlands Technology Foundation STW, the National Research Programme on Global Air Pollution and Climate Change NOP and by the European Space Agency ESA-ESTEC. We are very grateful for their support.

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1 Royal Netherlands Meterorological Institute KNMI
International research centre for telecommunications-transmission and radar IRCTR
Netherlands Energy Foundation ECN
National Institute of the Public Health and the Environment RIVM
Eindhoven University of Technology TUE
1 Introduction

Knowledge of cloud properties is needed for a number of applications:
• Climatology. The influence of clouds on the energy budget of the atmosphere is far from understood and causes a significant degree of uncertainty in the predictions of climate models. Especially the vertical structure of the radiative transfer in the atmosphere is important in this respect.
• Radio wave propagation. High-frequency radio signals are affected by clouds: attenuation and scintillation may occur due to absorption and cloud inhomogeneity.
• Environment studies. Anthropogenic aerosols may act as condensation nuclei and affect cloud formation.

The main gaps in existing knowledge are due to a lack of experimental data. To meet this deficit, research institutes and agencies are planning and performing a number of experiments to observe clouds. Lidars and mm-wave cloud radars are explored for their potential to measure cloud properties. The observation of vertical cloud structures with radar and lidar is a key element in the Earth Radiation Mission, that is now being considered by the European Space Agency.

In this report, a comparison is made between cloud observations with radar and lidar. On three days, with significantly different cloud types, collocated measurements with two lidars and the radar were performed. The measurements are compared with respect to the vertical structure: cloud base, cloud top and cloud thickness.

This study is related to the Clouds and Radiation campaign CLARA in which a number of Dutch research institutes (see Foreword) collaborate in an experiment to measure clouds and the interaction mechanisms with radiation. The lidar data is provided by the Royal Netherlands Meteorological Institute KNMI and the National Institute of Public Health and the Environment RIVM. The radar data is obtained with the Delft Atmospheric Research Radar of IRCTR.
2 The instruments

Introduction

Radar and lidar operate according to the same principle: they transmit an electromagnetic signal and measure that part of the signal that is scattered into the direction of the receiver. By measuring the time between transmission and reception, the distance of the scattering object is estimated. Scattering may be due to clouds, rain, aerosols or refractive-index fluctuations. In the next sections, the relevant properties of the radar and lidar will discussed.

The Delft Atmospheric Research Radar

The Delft Atmospheric Research Radar DARR is an S-band FM-CW Doppler radar. Compared with commonly used radars for cloud observations, DARR differs in two ways:
• it is an S-band system, operating at 3.315 GHz, whereas other cloud radars operate at frequencies above 35 GHz,
• it is an FM-CW system, whereas the common radar type uses pulse modulation of the radar signal. FM-CW radars are coherent by nature, and therefore able to measure the Doppler velocity spectrum.

<table>
<thead>
<tr>
<th>Radar type</th>
<th>FM-CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>3.315 GHz</td>
</tr>
<tr>
<td>Range resolution</td>
<td>30 or 15 m</td>
</tr>
<tr>
<td>Maximum unambiguous Doppler velocity</td>
<td>± 5 m/s</td>
</tr>
<tr>
<td>Doppler resolution</td>
<td>3.5 cm/s</td>
</tr>
<tr>
<td>Effective beamwidth</td>
<td>1.8°</td>
</tr>
<tr>
<td>Transmit power</td>
<td>80 or 100 W</td>
</tr>
<tr>
<td>Maximum height</td>
<td>8000 or 4000 m</td>
</tr>
<tr>
<td>Elevation</td>
<td>to zenith</td>
</tr>
<tr>
<td>Sensitivity at 1 km, 0 dB signal-to-noise</td>
<td>-35 dBZ</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>5.12 s</td>
</tr>
</tbody>
</table>

Table 1 The system parameters of DARR during the campaigns; the range resolution, transmit power and maximum height are selected on basis of the properties of the clouds that are measured.

The DARR is a flexible system. It is easy to vary system parameters like range resolution and sensitivity, which makes it suited for a wide range of applications. It has been used for atmospheric research since 1979, mainly dealing with precipitation, but over the last years cloud sensing has become the major application. In this study, the DARR was set up according to Table 1. The temporal resolution is determined by
post-processing. The sensitivity of -35 dBZ at 1 km corresponds roughly to a liquid water content of water clouds of 0.05-0.1 gm$^{-3}$.

DARR signal processing

A complete Doppler velocity spectrum, consisting of 256 samples, is measured. The Doppler spectrum is used to:

- filter noise: the uniform receiver noise is spread over the 256 samples of the Doppler spectrum, effectively increasing the signal-to-noise ratio per Doppler velocity cell with 27 dB ($=10 \log 256$). Now, if the desired signal due to cloud droplets only occupies a small portion of the total Doppler velocity spectrum, the overall signal-to-noise ratio is increased. Typical figures: a total spectrum width of 10 m/s versus a bandwidth of the cloud signal of 1 m/s, gives an improvement of 10 dB.
- for clutter suppression: clutter signals due to fixed objects like buildings appear in the Doppler spectrum as a strong peak at zero velocity, and are easily removed.

After filtering, the measured velocity spectrum $S(v)$ is used to calculate the reflectivity factor $Z_d$ according to

$$Z_d = \sum_k S(k\Delta v) \Delta v$$

where the summation is done over all Doppler resolution cells. The Doppler resolution is given by $\Delta v$. The radar also measures the mean velocity, and, when appropriate, separates bimodal Doppler spectra. For this study, however, only the measured reflectivity is used.

The lidars

A lidar operates according to the principle of pulse-radar, but instead of radio waves light waves are transmitted and received. A laser is used to transmit light in narrow pulses. With a detector the energy that is backscattered by a cloud is measured and related to the distance of the cloud by measuring the time-lapse between transmission and reception. Details of the lidars used in this study are given in Table 2. Different Vaisala-lidars were used on different occasions. The temporal resolution of the Vaisala-lidars is determined by integration of a number of height profiles and the time needed to apply the cloud base detection algorithms; the cloud top is not registered.
Table 2 Specifications of the lidar-ceilometers

<table>
<thead>
<tr>
<th>Type</th>
<th>Vaisala CT75K</th>
<th>Vaisala CT25</th>
<th>RIVM-lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>at radar site</td>
<td>at radar site</td>
<td>at radar site</td>
</tr>
<tr>
<td>Wavelength [nm]</td>
<td>905</td>
<td>905</td>
<td>1064</td>
</tr>
<tr>
<td>Range resolution [m]</td>
<td>15</td>
<td>15</td>
<td>1.5 (raw)</td>
</tr>
<tr>
<td>Beamwidth [mrad]</td>
<td>0.66</td>
<td>0.66</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum height [m]</td>
<td>12000</td>
<td>12000</td>
<td>7650 m</td>
</tr>
<tr>
<td>Elevation</td>
<td>to zenith</td>
<td>to zenith</td>
<td>to zenith</td>
</tr>
<tr>
<td>Temporal resolution [s]</td>
<td>30</td>
<td>45</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The Vaisala-system is designed to measure at least one cloud base. In case of optically thin clouds, a maximum of three cloud layers can be detected. The radar is located on the roof of the 100 m high building of Electrical Engineering of Delft University of Technology. It is operated by IRCTR. The Vaisala lidar is located at the radar site, and operated by the Royal Netherlands Meteorological Institute (KNMI).

On two occasions, the data of the RIVM-lidar was used in this study for comparison with the other systems. Most of the processing for this lidar is done off-line; raw data is collected during the measurements. For the analysis in this study the range resolution is set to 67.5 meter and the temporal resolution to 30 seconds.

To cross-check the range accuracy of the Vaisala-lidar and the radar an experiment was performed by pointing them at a chimney at a distance of approximately 1100 meter from the radar site: they agreed upon the distance of the chimney within 15 meter. Unfortunately, this experiment was not possible with the RIVM-lidar.

Supporting instruments

During the CLARA-campaigns other instruments were used as well. In this study, the data of an infra-red radiometer and of radiosondes were used during the analysis. The infrared radiometer measures the height-integrated down-welling radiation. In case of optically thick clouds, the measured infra-red sky temperature approximately equals the temperature at the cloud base. In case of optically thin clouds, the infra-red sky temperature is lower than that. By comparing the infra-red sky temperature with height profiles of the temperature measured by the radiosondes, distinction can be made between optically thin and optically thick clouds.
3 Scattering mechanisms

Particle scattering

A cloud consists of many droplets. When they are small compared to the wavelength, the back scatter is estimated with the Rayleigh-approximation. The reflectivity factor $Z_d$ is then related to the particle size $D$ through:

$$Z_d = \frac{1}{V} \sum_i D_i^6$$

where the summation is done over all particles in the radar resolution volume $V$. In the Rayleigh-regime, large particles reflect the radar waves more effectively than small particles. The reflectivity factor is strongly dependent on particle size; the Doppler spectrum is dominated by the large drops. The wavelength at which DARR operates is 9 cm, which ensures that the Rayleigh-approximation can be used. The received power $P^\text{rad}_r$ is given by

$$P^\text{rad}_r = C^\text{rad} \frac{K \Delta r}{R^2} Z_d$$

with

- $C^\text{rad}$ as the radar constant, that includes system characteristics as transmit power, wavelength and antenna pattern,
- $K$ as a factor that incorporates the refractive index of the scattering cloud droplets,
- $\Delta r$ as the radial range resolution of the radar, and
- $R$ as the distance of the radar volume under consideration: the received power decreases with the square of the distance.

In case of particles that are not small compared to the wavelength, more complex scattering theories apply. Scattering by spherical cloud droplets is described then by the Mie-theory; small particles can reflect the electromagnetic waves more effectively than large ones, due to resonance effects of the waves inside and diffraction around the particles. Also, with increasing frequency, signals are more attenuated by cloud droplets and rain. The quantitative interpretation of the measurements is much more complicated than in case of the Rayleigh-approximation. Mie-scattering occurs in case of the lidar-ceilometer. The lidar receives a power $P^\text{lid}_r$ given by
\[ P_r^{lid} = C_{lid} \frac{\Delta r}{R^2} \beta e^{-2\alpha} \]

in which the system parameters are lumped in \( C_{lid} \). The backscattering coefficient is given by \( \beta \). A major difference with the radar equation is the attenuation of the lidar signal, as given by \( \alpha \):

\[ \alpha = \int_0^R \sigma_{ext}(r) dr \]

with \( \sigma_{ext}(r) \) as the extinction of the lidar signal at position \( r \). When the attenuation between the cloud and the lidar is neglected, \( \alpha \) is determined by the penetration depth of the lidar signal in the cloud. The optical thickness \( \tau \) of the cloud can then be defined as:

\[ \tau = \int_{cloud base}^{cloud top} \sigma_{ext}(r) dr \]

In the optical limit, \( \sigma_{ext} \) is given by [van de Hulst, 1957]

\[ \sigma_{ext} = \frac{\pi}{2} \frac{1}{V} \sum_i D_i^2 \]

where the summation is done over all particles in the lidar resolution volume \( V \). The backscatter lidar signal is often caused by particles of different compound, e.g. aerosols and cloud droplets. The backscattered signal is therefore not easily inverted into for instance cloud liquid water content.

The extinction coefficient is not constant, but related to the backscatter coefficient [Stephens, 1994], as

\[ \beta = b \sigma_{ext}^n \]

for which the coefficients \( b \) and \( n \) can be derived from the Mie-theory. Assuming a relationship like equation 8 may enable the reconstruction of the true backscatter profile, which can then be used to determine the cloud base.
In the optical range multiple scattering may occur, due to the large concentration of cloud droplets, sample volume and wavelength [Ishimaru, 1978]. The waves only return to the receiver after having bounced several times between different cloud droplets. Due to the resulting time delay, the signal is interpreted as if it came from a larger distance than it actually is reflected from. The multiple scattering enhances the backscattered power, and consequently reduces the effect of extinction. It effectively broadens the lidar backscatter profile, which will be stretched away from the lidar. The relevance of multiple scattering to the observations described in this report has yet to be studied in detail. Preliminary calculations are discussed in [de Wolf, 1997]: it seems to be insignificant for cloud base detection with experimental set-up during the CLARA campaigns.

Clear-air scattering

At 3 GHz, the scattering process is complicated by possible gradients in the refractive index of the atmosphere. These gradients can be caused by transitions in temperature or humidity. Scattering by these irregularities is described by Tatarskii’s theory [1961] of scattering by isotropic turbulence, assuming gradual changes of the refractive index. The key parameter in this theory is the structure constant $C_n^2$, coming from

$$C_n^2 l^2 = \overline{(n(l) - n(l_0 + l))^2}$$

which equation gives the spatial variance of the refractive index $n$ at positions $l$ and $l + l_0$; the overbar indicates spatial integration. Radar scattering by a turbulent medium is dominated by fluctuations of the refractive index at a scale of half a wavelength, because signals that are scattered at these scales will coherently add up at the receive antenna. Inside clouds, this type of scattering may enhance the received power. Cloud boundaries can be accompanied by strong gradients of the refractive index (for instance due to temperature inversions). The scattering process may then appropriately be described by Fresnel scatter, in which not the structure constant but the reflection coefficient is the dominant term.

With high resolution Doppler processing the two scattering processes can under some circumstances be distinguished, because a turbulent spectrum will have a zero mean velocity, in contrast to the spectrum of cloud droplets. This form of processing has not been done for this study: it is mainly important for in depth cloud physics. Clear-air scattering does not play a role in the scattering process of the lidars used in this study.
4 Microwave and optical clouds

In the optical regime, cloud boundaries are easy to define, because they are visible with the naked eye. However, when instruments are used that operate at non-optical wavelengths, the matter of definition arises: what is a cloud? The simple definition is:

A cloud is a collection of particles in the sky. These particles can be water droplets, ice crystals, or (melting) snowflakes.

From a measurement point of view, this definition gives rise to several problems:
- What is a cloud boundary? Are, for instance, virga part of the clouds, and if so, is the cloud base then defined by the lower part of the virga? What happens in case of very light rain, when virga may actually precipitate on the ground? Clouds do not have to have well-defined boundaries. Usually, cloud boundaries are seen where the number concentration of particles is sufficient to scatter or absorb light waves effectively enough for the human eye. However, with radar the cloud boundaries may be seen at other positions, because of the different wavelength and so different scattering sensitivity to cloud droplets.

- How many droplets and of which size do we need before we speak of a cloud? This is a relevant question because different instruments are differently sensitive to the particle size. In case of Rayleigh scattering, back scattering is proportional to $D^6$, while in the optical regime it is proportional to $D^2$. So, a small number of sparsely distributed large drops may already give a large radar reflection, while the lidar may see nothing at all. Furthermore, due to the large difference in wavelength, the angular resolution of lidar and radar is different: lidars have beam widths of the order of tenths of a degree, whereas radars have beam widths of the order of 1 or 2 degree. The one-dimensional spot diameter $r$, the areal spot size $A$ and the resolution volume $V$ of the antenna or telescope beams are approximately given by

$$r = \theta \cdot R$$

$$A = \frac{1}{4} \pi (\theta \cdot R)^2$$

$$V = \frac{1}{4} \pi (\theta \cdot R)^2 \Delta r$$

with $\theta$ [rad] as the beam width of the antenna or telescope. The spot size increases with $R^2$: doubling the distance results in a 4 times increased spotsize. Table 3 gives some typical numbers for the instruments used in this study. Note the large differences between the two instruments!
Table 3  Spot diameter, spot size area and resolution volume of the radar and lidar; range resolution: 30 m; radar beamwidth: 1.8°; lidar beamwidth: 0.5 mrad.

Table 4 gives the drop concentration that is needed to cause the reflectivity level given in the first column, assuming that the radar volume is filled with cloud droplets of the same size. It shows that the radar reflectivity is very sensitive to the dropsize. A reflectivity of -30 dBZ can be caused by 10^9 drops of 10 μm, which is of the order occurring in stratus clouds, or by one droplet of 316 μm. This means that in case of precipitating or nearly precipitating clouds, the reflectivity may be dominated by a few large drops. It may be hard to distinguish the cloud base then. To the human eye 10^9/m³ drops appear as a nice cloud, but one drop of 316 μm will not be seen at all. Translated to the lidar: the number of such large particles in the lidar resolution volume, as given in Table 3, is small: only a few hundred, and may be too small to detect.

Table 4 also gives the optical thickness that corresponds to the reflectivity in the row above, for the given diameter and concentration, and assuming a cloud thickness of 500 m. For comparison: the sun becomes invisible behind clouds of optical thickness 10. The shaded part of the table gives the optically very thin clouds. Note that they are still very well distinguishable with radar.

Table 4  Necessary drop concentration to cause typical reflectivity levels as function of dropsize. The last column gives the diameter of a single drop that gives the reflectivity given in the first column. For each drop size and corresponding concentration the optical thickness is given. The grey part of the table indicates the optically very thin clouds. Assumed cloud thickness: 500 m.

It is clear that the above given definition of clouds will not help much to built up an expectation about the comparison of lidar and radar for cloud base detection. Experiments will help in that respect.
5 Vertical cloud structures

In stratocumulus clouds the liquid water content is often seen to increase with height [Martin et al, 1994] [Gerber, 1996] [Slingo et al, 1982]. This will have an impact on the vertical profiles of the lidar and radar signals, due to difference in different scattering mechanisms in the microwave and optical range. Let's assume an idealized cloud with an linearly increasing liquid water content and with the reasonable assumption of a constant number concentration inside the cloud [Frisch et al, 1995]. The peak heights in the lidar and radar profile are then given by:

\[ R_{\text{peak}}^{\text{radar}} = R_{\text{top}} \]

\[ R_{\text{peak}}^{\text{lidar}} = 0.3 \left( \frac{R_{\text{top}}}{LC_{\text{top}}} \right)^{2/3} \rho^{2/3} N^{2/3} \]

with

- \( R_{\text{top}} \) as the cloud top
- \( N \) as the number concentration
- \( \rho \) as the mass density of water.

The complete derivation is given in Appendix B. As a numerical example, assume:

- \( R_{\text{top}} = 500 \text{ m} \)
- \( LWC_{\text{top}} = 0.5 \text{ gm}^{-3} \)
- \( N = 500 \cdot 10^6 \text{ m}^{-3} \)
- \( \rho = 10^6 \text{ gm}^{-3} \)

then we get \( R_{\text{peak}}^{\text{lidar}} \approx 22 \text{ m} \) and \( R_{\text{peak}}^{\text{radar}} = 500 \text{ m} \).

Thus, the height distribution of the liquid water content influences the estimates of the cloud boundaries. The lidar will get a peak from the lower parts of the clouds, whereas the radar receives one from the cloud top. Not always, the water content increases with height: for instance in ice clouds, the water content is sometimes seen to decrease with height [e.g. Matrosov et al, 1995]. The extinction and backscatter profiles are both monotonously decreasing function of height then. The radar and lidar will both get a peak from the lower part of the cloud.

This asymmetry has some implications for space-based systems. In cumuli-form clouds the liquid water increases with height: the space-based radar and lidar will both
get a peak from the cloud top. For clouds types with the maximum liquid water content at the bottom, the space-based radar will get a peak from the cloud bottom and the lidar from the cloud top.

The actual situation is of course more complex than these idealized clouds. The concentration is not constant and the height dependence of the liquid water content is never truly linear, but the idealization clearly shows a trend. Maybe, the combination of radar and lidar can be used to derive the vertical distribution of water in the clouds.
6 Definitions of the cloud base and top

The Vaisala-instrument is equipped with a real time cloud-base detection routine; it does not calculate a cloud top. As a result of company policy, details of this routine are not known to the authors. However, the measured backscatter profiles are available for the development of alternative algorithms. In this study, the following definitions of the cloud base and top are used:

- the cloud base is defined at the height below the peak in the height profile where 10% of the maximum power is coming from

- the cloud top is defined at the height above the peak in the height profile where 10% of the maximum power is coming from

- the cloud width is defined as the difference between the cloud top and cloud base

The same definitions were used for the radar measurements.
7 Measurements

Three examples of significantly different situations will be discussed. In Table 5 relevant details are given. Colour pictures of the measurements are given in Appendix A.

<table>
<thead>
<tr>
<th>Date</th>
<th>time (UTC)</th>
<th>cloud type</th>
<th>remarks</th>
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<tbody>
<tr>
<td>April 18, 1996</td>
<td>20.00 - 01.00</td>
<td>altostratus</td>
<td>ice</td>
</tr>
<tr>
<td>April 19, 1996</td>
<td>06.30 - 12.00</td>
<td>stratocumulus</td>
<td>thin layer</td>
</tr>
<tr>
<td>September 4, 1996</td>
<td>08.30 - 10.00</td>
<td>stratocumulus</td>
<td>drizzle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>used lidars</th>
</tr>
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<tbody>
<tr>
<td>April 18, 1996</td>
<td>Vaisala CT75K, RIVM</td>
</tr>
<tr>
<td>April 19, 1996</td>
<td>Vaisala CT75K, RIVM</td>
</tr>
<tr>
<td>September 4, 1996</td>
<td>Vasala CT25</td>
</tr>
</tbody>
</table>

*Table 5 Details of the selected measurements*
Case 1: Stratocumulus and cumulus

Figure 1  Height-time diagram of the radar reflectivity and Vaisala lidar backscatter on April 19, 1996; the black contour lines represent the lidar backscatter.
Figure 1 shows the radar reflectivity and the lidar backscatter as function of time. Throughout the measurement, a thin cloud layer is observed at approximately 1700 meter. The stratocumulus field was not entirely overcast: every now and then holes occurred in the cloud deck. The concurrent infra-red radiometer measurements showed a large scatter, which also indicates a broken cloud layer. In the second half of the measurement, the convective activity in the boundary layer is increasing as can be recognized in the enhanced speckle patterns in the radar plot: the cloud layer breaks up in separate cumuli. The fact that the radar and lidar, in the first part of the observation period, seem to observe a closed cloud layer is due to a combination of resolution and integration time.

Figure 2 shows a typical height profile of the radar reflectivity and of the two lidar systems.

![Graph](image)

**Figure 2**  *Examples of the height profiles of the radar and lidar data, taken on April 19, 1996.*

The differences between the height profiles are intriguing. Each system gives a different cloud height. The radar sees a cloud that is approximately 100 meter higher than that the lidars do. The RIVM-lidar gets its backscatter from lower heights than the Vaisala lidar. These measurements seem to justify the rough calculations of peak heights in section 5, assuming a liquid water content that increases with height. The differences between the two lidar systems can possibly be attributed to the difference in wavelengths. One might ask: does the radar observe a cloud, or maybe something
else due to clear air scattering? During the measurements in situ dropsize measurements were done; unfortunately, the aircraft took its data some 30 km away from the radar site. Using these dropsizes, the expected radar reflectivities were calculated and compared with the actually measured ones. The calculated reflectivities were significantly smaller than the values the radar observed, but still well above the detection limit of the radar system.

The detected cloud width of the radar and Vaisala-lidar are different, as can be seen in Figure 3. The cloud base and top are for both instruments defined as the height where 10 % of the peak reflection is coming from. The radar sees a significantly smaller cloud layer than the lidar, and due to larger sample volume of the radar, less variation.

![Cloudwidth by Radar and Lidar](image)

**Figure 3**  Radar and lidar derived cloud width; April 19, 1996

As explained before, the 3 GHz system may be sensitive to spatial variations temperature and water vapour inside the clouds. The presence of this Bragg scatter can be clarified by comparing the peak reflections of the radar and lidar height profiles as function of time. The lidar reflection is only due to particle backscatter, whereas the radar reflection is due to particle as well as Bragg scatter. Figure 4 shows the result of comparison the two profiles.
Figure 4  Time dependence of the peak reflections in the radar and lidar profiles

The two peak reflections show a reasonable temporal correlation, although significant smoothing was necessary to visualize it. The correlation is interesting, especially because the peak reflections of the two instruments originate from different heights. Apparently, the reflection at the cloud top is correlated to the reflection stemming from the lower parts of the cloud. In classical cloud models, the concentration of particles is determined by the number of aerosols at the cloud base, and the droplets grow while they ascend towards the cloud top. The correlation in Figure 4 seems to confirm: if the concentration varied significantly within the cloud, the reflection at the cloud top and cloud base would be decorrelated. Furthermore, if Bragg scatter dominates the radar return, then such a high positive correlation is not to be expected.
Case 2: Altostratus

Figure 5  Height-time diagram of the radar reflectivity and Vaisala lidar backscatter on April 18, 1996; the black contour lines represent the lidar backscatter.
Figure 5 shows the radar reflectivity and the lidar backscatter as function of height and time. A thick layer occurs between 2500 and 5000 meter. The lidar and radar coincide reasonably, although at some instances the radar does not observe a cloud, while the lidar still does. The isolated reflections underneath the cloud layer are still of unknown origin, but are often seen in case of wind coming from the North Sea. Probably, they are due to clear air scattering.

Radiosonde measurements were done at 18 utc. The temperature at 2500 meter was approximately 0 °C and -15 °C at 5000 meter. The infrared radiometer, however, showed temperatures between -10 and -30 °C. The temperature sensed by the infrared radiometer was not the same as the temperature at the cloud base, which indicates that the cloud had a low emissivity and was optically not very thick.

Figure 6 shows some typical height profiles of the two lidars and the radar.

Figure 6  Examples of the height profiles of the lidars and the radar, taken on April 18, 1996.

The radar reflectivity is much larger in comparison with Figure 2, and the lidar backscatter is much smaller. The large radar reflectivity indicates the presence of ice crystals: it can not be caused by small water droplets, unless it is an optically very thick cloud, but that would have resulted in a large lidar signal as well (see also Table 4). The radar peak is located below the lidar peaks, and the shape of the profiles is in reasonable agreement.
Figure 7 shows from which height the lidar and radar receive the maximum power, throughout the observation time.

![Comparison of peak locations in radar and lidar profiles](image)

**Figure 7**  *The location of the peaks in the radar and Vaisala-lidar profiles.*

At the beginning of the measurement, the lidar receives its maximum from larger heights than the radar, during other periods the radar peak is located higher than the lidar peak, and also periods that the two instruments give similar peak heights occur.

Figure 8 shows the cloud base of radar and Vaisala lidar. The factory algorithm of the lidar did not calculate a cloud base: we have defined the cloud base at the height where 10% of the peak reflection is coming from. The radar and lidar are in good agreement with each other, although the radar estimates the cloud base a bit higher. The temporal correlation between the two signals is striking.
Figure 8  Comparison of the lidar and radar derived cloud base. In both cases, the cloud base is defined as the height where 10% of the peak reflection is coming from.

Figure 9  Comparison of the lidar and radar derived cloud width.

Figure 9 shows the cloud width, derived from the radar and Vaisala-lidar data. The temporal correlation is good, but at some instances differences of a few hundred meter can occur. During several periods, the lidar derives a larger cloud width than the radar.
Case 3  Stratocumulus and drizzle

Figure 10  Height-time diagram of the radar reflectivity and Vaisala lidar backscatter on September 4, 1996; the black contour lines represent the lidar backscatter.
Drizzle and light rain dominated the weather. On the radar plot isolated drizzle clouds occur. The radar and lidar both see a layer at approximately 350 meter. The radar, however, also observes clouds at other heights. On some occasions the lidar observes "clouds" at higher levels. This occurs when the radar indicates little rain: the lidar is then able to penetrate deeper into the atmosphere. Figures 11 shows lidar and radar height profiles, taken during the first part of the observation time.

![Graph showing lidar and radar height profiles](image)

**Figure 11 Height profile of the radar and Vaisala-lidar on September 4, 1996; first part of the measurement**

The radar and lidar profiles are very different: the radar measures a cloud between 500 and 1000 meter and some weak reflections below the cloud, due to drizzle. The lidar receives a peak from the bottom of the cloud, but also a few peaks occur beneath the cloud. A close inspection shows that these peaks are correlated with small enhancements of the radar reflectivity.

The particle concentration in drizzle or light rain is much smaller than in clouds, which would normally result in a very small optical thickness (see Table 4). The spiky appearance of the height profile suggests that every now and then a few larger drops are hit by the laser beam of the lidar.

Figure 12 show the height profiles taken during the middle part of the measurement.
Figure 12 Height profile of the radar and Vaisala-lidar on September 4, 1996; middle part of the measurement

The radar measures two small clouds between 500 and 1000 meter. In the lidar profiles peaks occur at the bases of the two clouds. Note that the upper lidar peak is much stronger than the lower one, whereas the 'radar clouds' show the opposite behaviour.

Figure 13 shows the height profile taken during the last part of the measurement. Again the lidar sees two peaks: one coincides with the cloud base as seen by the radar, and one that coincides with a transition inside the 'radar' cloud. The fact that the lidar penetrates inside the clouds and even detects different layers inside the clouds shows that the extinction in these types of clouds is not large enough to absorb the laser energy completely.
The spiky appearance of the lidar measurements raises the issue of temporal variability. Figure 14 shows three succeeding height profiles of the lidar, measured with time gaps of approximately 45 seconds. The profiles are taken from the first part of the event. The peaks at ± 700 and ± 200 meter are reasonably persistent, but highly variable in strength; at 400 meter suddenly a peak occurs. The upper peaks correspond to the cloud layer that was also observed by the radar. The same behaviour was observed in the middle part of the cloud: large temporal variability of the strength of the lidar signal due to clouds and peaks may occur at other heights quite randomly. At the final part of the cloud, however, the lidar peaks nicely coincide with the radar clouds, although the strength of the peaks is quite variable again (see Figure 15).
Figure 14 Three succeeding height profiles of the lidar signal, taken during drizzle.

Obviously, determining the cloud base and top from lidar data like this is not self-evident. The definitions we use will select a peak that may not have anything to do with the cloud. The same, although to a lesser degree, holds true to the radar: drizzle or rain may give larger reflections than the cloud it is coming from. In Figure 16 the radar derived cloud base and top is given. The cloud varies between 800 and 100 meter; the cloud base is much more variable than the cloud top. The histograms of the cloud base, derived with radar and lidar, in Figure 17 are rather flat. The span of derived cloud bases is approximately 1000 meter for both instruments, although the histogram of the lidar is shifted towards lower values compared to the radar.
Figure 15 Three succeeding height profiles of the lidar, taken during cloudy conditions; little drizzle.

Figure 16 Radar cloud top and base; September 4, 1996, 08.30-10.00 utc
Figure 17  Histogram of radar and lidar cloud base; September 4, 1996, 08.30-10.00 utc
8 Conclusions

During most of the observations discussed in this report, the lidar and radar measurements are in good agreement with respect to the cloud base and top. The determination of the cloud base and top is, however, not self-evident. The lidar signal from clouds is due to Mie-scattering and the radar signal is due to Rayleigh-scattering, which makes the two instruments differently sensitive to the size of the cloud droplets, and consequently to the vertical distribution of water or ice inside the cloud. In case of clouds in which the water content increases with height, the radar receives its maximum from the upper half of the cloud. In case of a water content that decreases with height, the radar will see a peak in the lower parts of the clouds. The extinction of the lidar signal will in these cases result in a peak somewhere in the lower part of the cloud. This issue has been illustrated with two examples, but has to be studied in more detail. It may possibly be used to derive the vertical distribution of water and ice, and even to distinguish water from ice clouds.

Sometimes the lidar observes a higher cloud top than the radar, which is not in agreement with the perception that extinction dominates a lidar signal. In these cases, multiple scattering may occur, that virtually broadens the cloud. This issue has to be studied in more depth.

In case of drizzle, the lidar signal becomes 'spiky', probably due to local inhomogeneities in the clouds: the laser beam may hit isolated drops, or clusters of drops.
9 Recommendations

In this study only a few measurements are analyzed. It is recommended to analyze more data, for instance from the CLARA data set, aiming at:

• in depth understanding of the vertical structure as radar and lidar measure it;
• the significance of multiple scattering;
• sensor synergy to obtain the vertical distribution of water inside the clouds;
• the potential to discriminate water and ice using radar and lidar;
• the conversion of ground-based derived results and algorithms for space-based applications,
• the development of methods to retrieve microphysical cloud properties.
10 References

Hulst, H.C. van den, 1957, 'Light scattering in small particles', Dover, New York, 470pp
Appendix A Colour plates of the measurements

18 and 19 April 1996

Delft Atmospheric Research Radar
ESA/Vaisala lidar CT75

4 September 1996

Delft Atmospheric Research Radar
KNMI/Vaisala lidar CT25
Appendix B
Simplified approach to calculate peak heights in lidar spectra

Assume a simple cloud in which the liquid water content \( LWC \) linearly increases with height \( h \):

\[
LWC = \alpha h \quad \text{[gm}^{-3}\text{]}  
\]

\[
\alpha = \frac{LWC_{top}}{H_{top}} \quad \text{[gm}^{-4}\text{]}  
\]

with \( H_{top} \) as the cloud top and \( LWC_{top} \) as the liquid water content at the top of the cloud. In the optical limit the backscatter and extinction coefficient \( \beta \) and \( \sigma \) are given by:

\[
\beta = \sigma = \frac{\pi}{2} N D^2 \quad \text{[m}^{-1}\text{]}  
\]

with \( N \) \([m}^{-3}\text{]} \) as the number of droplets and \( D \) \([m]\) as the mean drop diameter. The liquid water content is given by, with \( \rho \) \([gm}^{-3}\text{]} \) as the mass density of water:

\[
LWC = \frac{\pi}{6} N D^3 \rho \quad \text{[gm}^{-3}\text{]}  
\]

If we assume that a constant number concentration, we get:

\[
D = \left[ \frac{6}{\pi \rho} \frac{1}{N} LWC \right]^{\frac{1}{3}}  
\]

and consequently:

\[
D = \left[ \frac{6}{\pi \rho} \frac{1}{N} \alpha h \right]^{\frac{1}{3}}  
\]

The backscatter and extinction coefficient can now be written as:
\[
\beta = \sigma = \frac{\pi}{2} \left[ \frac{6}{\pi \rho} \right]^\frac{3}{4} N^\frac{1}{2} \alpha^\frac{1}{4} h^{\frac{3}{4}} = \gamma h^\frac{3}{4}
\]

with

\[
\gamma = \frac{\pi}{2} \left[ \frac{6}{\pi \rho} \right]^\frac{3}{4} N^\frac{1}{2} \alpha^\frac{1}{2}
\]

The received power \( p(h) \) is related to the backscatter and extinction as:

\[
p(h) \sim \beta(h) e^{-2\sigma(h) dh}
\]

The peak of the profile is determined by:

\[
\frac{\partial p(h)}{\partial h} = \frac{\partial \beta(h)}{\partial h} e^{-2\sigma(h) dh} - 2\sigma(h)\beta(h) e^{-2\sigma(h) dh} = 0
\]

which gives:

\[
\frac{\partial \beta(h)}{\partial h} - 2\sigma(h)\beta(h) = 0
\]

\[
\frac{\partial \beta(h)}{\partial h} = \frac{2}{3} \gamma h^{-\frac{1}{4}}
\]

\[
h_{\text{max}} = \left[ \frac{1}{3 \gamma} \right]^{\frac{1}{2}}
\]

resulting in:

\[
h_{\text{max}} = 0.3 \left[ \frac{H_{\text{top}}}{LW \cdot C_{\text{top}}} \right]^{\frac{1}{2}} \frac{\rho^\frac{1}{4}}{N^\frac{1}{4}}
\]
When the optical thickness increases (increasing $LWC_{\text{top}}$ and/or $N$), $h_{\text{max}}$ decreases: the peak shifts to the cloud bottom. A numerical example:

$H_{\text{top}} = 500$ m

$LWC_{\text{top}} = 0.5 \text{ gm}^{-3}$

$N = 500 \cdot 10^6 \text{ m}^{-3}$

$\rho = 10^6 \text{ gm}^{-3}$

$\rightarrow h_{\text{max}} \approx 22$ m.

What if the particle size in the cloud is constant, and the liquid water content variation is determined by a varying number concentration instead? We then get:

$$N = \frac{6}{\pi \rho} \frac{LWC}{D^3}$$

and after following the same procedure:

$$h_{\text{max}} = \left[ \frac{\rho D}{6} \frac{H_{\text{top}}}{LWC_{\text{top}}} \right]^\frac{1}{2}$$

For $D = 10 \mu$ and the other parameters the same as above, we get $h_{\text{max}} = 41$ m: again near the cloud bottom.

The 3 GHz radar signal is not attenuated. The peak in the radar profile will therefore coincide with the peak in the liquid water profile: at the top of the cloud. In case of a 94 GHz radar, attenuation occurs and the peak in the profile does not have to coincide with the height of maximum water content. However, it is unlikely that the lidar and radar peaks coincide. The difference in peak heights can possibly be used to parameterize the vertical distribution of liquid water content inside the cloud.

In a cloud in which the water content decreases with height, the backscatter and extinction profiles are monotonously decreasing with height. The lidar and radar will both observe a peak at the bottom of the cloud.