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Algorithms for determining water vapour and liquid water contents of the atmosphere using radiometer and meteorological data

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Table of contents

1. *Introduction*

Microwave radiometry has been a topic of research within the Radio communications Group for some time now. The objective of the research activities is to find a reliable and cost-effective way to determine water vapour and liquid water contents of the troposphere. Applications for this kind of measurements are within the design of satellite communication systems, meteorological and environmental research of the atmosphere and clouds in particular.

The remote sensing technique described in this report is based on the measurement of the brightness temperatures at two different frequencies (21.3 GHz and 31.7 GHz) with a radiometer. From these measurement data it is possible to determine the integrated liquid water (L) and integrated water vapour (V) of the atmosphere using special algorithms. For the most simple retrieval algorithms V and L are estimated by a linear combination of the atmospheric attenuations at 21.3 GHz and 31.7 GHz. The linear algorithms described in this report are CCIR (using no actual meteorological data), SIGMA-A (using actual ground-values for temperature and pressure) and SIGMA-B (which only uses the known annual periodicity of these meteorological parameters). These algorithms were developed by comparing the retrieved V and L values with the values derived from a large set of radiosonde measurements. (It may be useful to remark that the CCIR recently changed its name to ITU-R, throughout this report, however, the old name is used).

A more sophisticated way to determine V and L is the so called 'matched atmosphere' algorithm. In this calculation method the ground meteorological data are used as a basis to tune the temperature (T) and air pressure (P) profiles of the CCIR standard atmosphere together with the relative humidity profile (RH) according to Peter and Kämpfer [7]. Cloud base height and a relative humidity reference level are parameters to be varied until the brightness temperatures calculated from the atmosphere model match the measured temperatures as closely as possible. Having found the best match, L and V can be calculated from this atmosphere model. Benefits of this method are, that it is more physical and it is possible to gain insight in the calculation of V and L, and it is more dynamic so extreme situations can be handled more better. By using real-time meteorological data to make a reconstruction of the actual atmosphere we hope to get a retrieval method that is more accurate than the linear retrieval algorithms.

Within the framework of the research on CLouds And RAdiation (CLARA) a number of measurement campaigns are done by TU-Delft, FEL-TNO, RIVM, ECN and KNMI. The Eindhoven University of Technology is participating in this project with radiometer measurements. During the campaigns a lot of data about the atmosphere and clouds in particular are gathered using the following measuring equipment : radar, lidar, infrared radiometer and radiosondes. Also measurements are done by flying through the clouds and determining a distribution of the water droplets (size and number). The information obtained from all these measurements like cloud base, cloud top and atmosphere profiles, offers the unique opportunity to verify the models used.

For the periods that radiosonde data are available, real atmosphere profiles are available which can be used in the Matched Atmosphere Algorithm instead of the CCIR standard atmosphere. In this way it is expected that a more accurate V and L retrieval is possible in these cases.
The aim is to use the information obtained from all measurements to verify how accurate the V and L retrieval algorithms are. When this is examined for the previously mentioned algorithms, then next step will be to search for new and better (in the sense of accuracy or calculation speed) algorithms in literature.

Chapter 2 of this report gives a survey of the principles of radiometry. In Chapter 3 the algorithms to retrieve the integrated amount of water vapour and liquid water from radiometric measurements are described. As was said before, there are linear algorithms and the so-called Matched Atmosphere Algorithm. In the Matched Atmosphere Algorithm more information about the atmosphere, such as cloud base height or radiosonde profiles is used. How the different algorithms are implemented and how additional information can be used is described in Chapter 4. The results of water vapour and water liquid calculations using the different algorithms are compared in Chapter 5. In Chapter 6 the sensitivity of the Matched Atmosphere Algorithm to variations in the different parameters and profiles is looked at in more detail. A comparison between calculated amounts of water vapour and liquid water with their corresponding reference values is made in Chapter 7. Finally, in Chapter 8 conclusions are drawn and some recommendations are made.

2. *Principles of radiometry*

The purpose of this chapter is to give a brief survey of the theory of radiometry and to give more insight in the measurements and the deviation of the different algorithms.

2.1 Atmospheric brightness temperature

The atmosphere is an absorbing medium. In the frequency range from 20 GHz up to 50 GHz most of the absorption is caused by liquid water, water vapour and oxygen. All energy absorbed is emitted again, as stated by Kirchhoff's law. This property makes it possible to measure characteristics of the atmosphere with a radiometer.
Planck stated that for all 'black bodies' (objects that absorb all incident radiation) the radiated power per unit area, solid angle and bandwidth, called *spectral brightness* B_f is given by the next formula:

$$B_f = \frac{2h_p f^3}{c^2} \frac{1}{\exp\left(\frac{h_p f}{kT}\right) - 1} \qquad \left[\frac{W}{m^2\ sr\ Hz}\right] \qquad (2.1)$$

where: h_p *is Planck's constant*, $6.626 \cdot 10^{-34}$ *Js*
f is the frequency in Hz
k is Boltzmann's constant, $1.38 \cdot 10^{-23}$ *J/K*
T it the absolute temperature in K
c is the speed of light in m/s.

As shown in [1] for frequencies in the microwave range (up to 100 GHz) the so-called Rayleigh-Jeans approximation can be used. It introduces a deviation of not more than 5% on power density.

$$B_f = \frac{2f^2kT}{c^2} \qquad \left[\frac{W}{m^2\ sr\ Hz}\right] \qquad (2.2)$$

A black body exists only in theory; in practice objects only absorb part of the incident radiation and therefore are called 'grey'. The *brightness temperature* of a grey body is defined as the physical temperature *T* of a black body emitting the same power.

Thus for real 'grey' objects the spectral brightness is given by:

$$B_f = \frac{2f^2kT_b}{c^2} \qquad \left[\frac{W}{m^2\ sr\ Hz}\right] \qquad (2.3)$$

where: T_b *is the brightness temperature in K*

The atmosphere can be considered as a 'grey body'. As the atmosphere is in general inhomogeneous it is divided in a large number of layers with a certain thickness. Each of these layers is taken to be homogeneous and to have a constant temperature. The troposphere now exists of thin layers within which the absorption is constant. This leads to the model as shown in Figure 2.1.

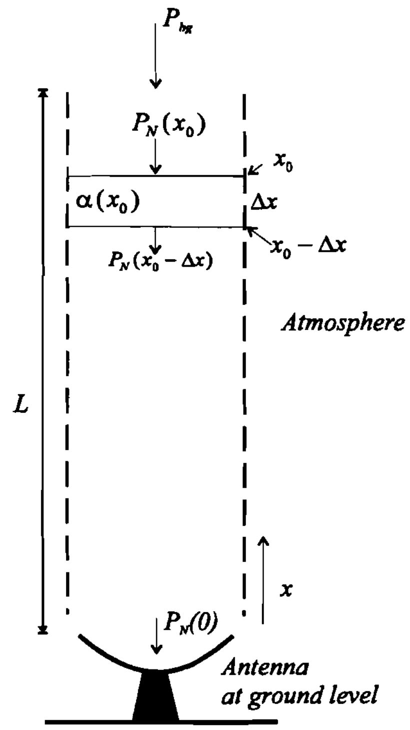


Figure 2.1 Transfer model of the atmosphere.

In this figure is:

P_{bg}	*the cosmic background noise power entering the atmosphere,* $P_{bg} = P_N(L)$
L	*total thickness of the atmosphere (taken to be 12 km in our calculations)*
$P_N(0)$	*the resulting noise power at the antenna,*
$P_N(x)$	*the noise power at a distance x,*
$\alpha(x)$	*the absorption coefficient*
	$\alpha_{Np}(x) = \ln(\alpha(x))$ *is the absorption coefficient in Np/m*
Δx	*the thickness of one layer*

The absorption coefficient $\alpha(x)$ is defined as the part of the power that is absorbed per unit distance:

$$\alpha(x_0) = \frac{P_N(x_0) - P_N(x_0 - \Delta x)}{P_N(x_0)\Delta x} \tag{2.4}$$

The power absorption of each of the thin homogeneous layers can now be written as:

$$P_N(x - \Delta x) = P_N(x) - \alpha(x)\Delta x P_N(x) \tag{2.5}$$

According to Kirchhoff's law the absorbed power is emitted again. By applying the Rayleigh-Jeans approximation and writing this expression in terms of noise temperatures we obtain:

$$T_N(x-\Delta x) = \left(1-\alpha(x)\Delta x\right)T_N(x) + \alpha(x)\Delta x T(x) \qquad (2.6)$$

where: *$T(x)$ is the physical temperature of the atmosphere layer at height x*
$T_N(x)$ is the noise temperature of the atmosphere layer at height x

It can be seen that there is one term representing the absorption and a second term which represents the emission.

When the layer thickness approaches zero this leads to the following differential equation:

$$\frac{dT_N(x)}{dx} - \alpha(x)T_N(x) = \alpha(x)T(x) \qquad (2.7)$$

When this equation is solved, this leads to the conclusion that the antenna noise power of an ideal 'pencil-beam' radiometer antenna can be related to T_b. For a non-scattering atmosphere this is done by the following *radiative transfer equation*:

$$T_b = T_{bg}\ e^{-\tau(0,L)} + \int_0^L \alpha(x')T(x')\ e^{-\tau(0,x')}\ dx' \qquad (2.8)$$

where: *T_b is the brightness temperature at the antenna in K; $T_b=T_N(0)$.*
T_{bg} is the cosmic background noise temperature in K,
τ is the optical thickness defined as: $\tau(x',x) = \int_{x'}^{x} \alpha(s)ds$
$T(x')$ is the physical temperature at a height x',

The assumption of the atmosphere being non scattering is legitimate when there is no precipation or with low rain rates, according to [1 section 2.1]. From Equation (2.8) can be seen that T_b is composed of one term representing the cosmic background brightness and another due to atmospheric emission. Furthermore, it is clear from this equation that T_b depends on vertical temperature and absorption profiles.

When the atmospheric temperature and absorption are taken to be constant this leads to the following expression for the brightness temperature:

$$T_b = T_{bg}e^{-\alpha L} + T_{eff}(1-e^{-\alpha L}) \qquad (2.9)$$

where: *T_{eff} is constant; the effective temperature of the atmosphere*

Since the total attenuation in case of a constant absorption is equal to the absorption coefficient α multiplied by the total path lenght L. The total attenuation A can therefore be expressed as:

$$A = 10\log\frac{T_{eff} - T_{bg}}{T_{eff} - T_b} \qquad [\text{dB}] \qquad (2.10)$$

When the relevant atmospheric profiles are known it is also possible to calculate the brightness temperature from these. This is called the *direct problem*. With remote sensing the opposite is the case; the aim here is to derive atmospherical characteristics (in our case liquid water content and water vapour) from the measured brightness temperature. This is called the *inverse problem*.

2.2 *Millimeter wave propagation model*

The millimeter wave propagation model (MPM) discussed here was developed by H.J. Liebe. He first published it in 1985. This report uses the version of MPM as it was presented in [2] in 1989. The model predicts the effects on radio waves as loss and delay caused by the atmosphere for frequencies up to 1000 GHz . Contributions from dry air (oxygen), suspended water droplets (hydrosols: haze, fog and clouds) and rain are taken into account. In our applications the MPM is used to calculate brightness temperatures and attenuation of an atmosphere.

2.2.1 *Input profiles and parameters*

The input data MPM uses to characterise the atmosphere are the height profiles from 0 up to 30 km of:

- pressure; *P(h)*,
- temperature; *T(h)* and
- relative humidity; *RH(h)*.

These profiles can be obtained from radiosonde data in which case a rather accurate characterisation of the atmosphere is available. But MPM might as well be used to calculate the characteristics of a modelled atmosphere by using estimated profiles (based on, for instance, ground values of *T*, *P* and *RH*).

From the input profiles the following internal parameters can be derived:

$$p=P-e \qquad (2.11)$$

where: *P is the barometric pressure in [kPa],*
e is the partial water vapour pressure in [kPa],
p is the dry air pressure in [kPa].

$$\theta = \frac{300}{T} \qquad (2.12)$$

where: *θ is the relative inverse temperature in K^{-1}*
T is the temperature in K

$$e = e_s \cdot \frac{RH}{100} \qquad (2.13)$$

where: *e is the partial water vapour pressure in kPa*
e_s is the water vapour saturation pressure in kPa
RH is the relative humidity in %,

Using empirical methods Liebe found the following expression for the water vapour density (v):

$$v=7.223\, e\, \theta \qquad [g/m^3] \qquad (2.14)$$

Also an approximation for the temperature dependence of water vapour saturation pressure e_s was found for temperatures from -40°C up to +40°C with an error smaller than 0.2%. Expressed as water vapour concentration this results in:

$$v = 1.739 \cdot 10^9 \; RH \; \theta^5 \; \exp(-22.64 \cdot \theta) \qquad [\text{g/m}^3] \qquad (2.15)$$

The integrated water vapour (V) can be calculated from v according to:

$$V = \frac{100}{\rho_w} \int_0^\infty v(h)dh \qquad [\text{cm}] \qquad (2.16)$$

where: *ρ_w is the specific weight of water, 10^6 g/m^3*
h is the path through the atmosphere in km.

The liquid water density (w) is found to be composed of three contributions:

$$w = w_C + w_A + w_R \qquad [\text{g/m}^3] \qquad (2.17)$$

where: *w_C is the liquid water density contribution of clouds in g/m^3*
w_A is the liquid water density contribution of hydroscopic aerosols in g/m^3
w_R is the liquid water density contribution due to rain in g/m^3.

The concentration of hydroscopic aerosols in the atmosphere is related to the relative humidity. Solution droplets appear for *80% < RH < 99.9%* and can reach concentrations up to *0.1 g/m^3*. The suspended droplet concentration due to aerosols (w_A) is modelled by Liebe as follows:

$$w_A = 0 \qquad (\text{for } 0\% \le RH < 80\%)$$

$$w_A = w_0 \cdot \frac{20 \cdot (C_1 + 4) - RH}{C_1 \cdot (100 - RH)} \qquad (\text{for } 80\% \le RH < 99.9\%) \qquad [\text{g/m}^3] \qquad (2.18)$$

where: *w_0 is the dry mass concentration of hydroscopic aerosols in g/m^3*
C_1 a parameter that depends on the particular location:

Rural environment:	*C_1=1.87*
Urban environment:	*C_1=2.41*
Maritime environment:	*C_1=5.31*
Maritime and a strong wind:	*C_1=5.83*

Liebe's model assumes there is a cloud whenever the relative humidity is 100%. The contribution of clouds to the liquid water density can be deduced from the drop size spectra. As this information is often not available, this contribution has to be obtained in another way. Therefore the model by Slobin [3] is used which gives the following expression for the liquid water density profile:

$$w_C(h) = C \cdot (\rho_{base} - \rho_{top}) \cdot \left(\frac{h - H_{base}}{H_{top} - H_{base}} \right) \qquad [\text{g/m}^3] \qquad (2.19)$$

where: *ρ_{base} is the saturated water vapour density at the base of the cloud in g/m^3*
ρ_{top} is the saturated water vapour density at the top of the cloud in g/m^3

$$\rho(h) = 1.739 \cdot 10^{11} \cdot \theta^5(h) \cdot \exp(-22.64 \cdot \theta(h))$$

h is the height in m
C is a tuning parameter depending on the type of cloud, typical between 0.1 and 0.7

In the eventual algorithm H_{top} , H_{base} and C have to be chosen in such a way that they match the actual values as closely as possible. If radar or lidar data are available H_{top} and H_{base} can be obtained from that.

Finally the liquid water density due to rain is given by:

$$w_R(h) = Rr \cdot mR \qquad for\ 0 \leq h \leq H_{top} \qquad [g/m^3] \qquad (2.20)$$

where:

Rr is the rain rate in mm/hour, which must be less then 200 for this approximation to apply. For higher rain rates scattering is not negligible anymore.

mR is an empirically determined constant:

mR=0.1	*for* $0 \leq Rr \leq 2.5$ *mm/hour*
mR=0.07	*for* $2.5 \leq Rr \leq 12.5$ *mm/hour*
mR=0.05	*for* $12.5 \leq Rr \leq 110$ *mm/hour*
mR=0.04	*for* $110 \leq Rr \leq 200$ *mm/hour*

The integrated liquid water contents (L) can be calculated by integrating w over the path through the atmosphere:

$$L = \frac{100}{\rho_w}\int_0^{\infty} w(h)dh \qquad [cm] \qquad (2.21)$$

2.2.2 *Refractivity contributions*

According to MPM the attenuation can be calculated from the *complex dispersive refractivity $N_t(f)$*:

$$N_t(f) = N_0 + N(f) = N_0 + N'(f) - jN''(f) \qquad [ppm] \qquad (2.22)$$

The attenuation is determined by the imaginary part, $N''(f)$, which can be represented by five terms:

$$N'' = N''_L + N''_d + N''_c + N''_w + N''_R \qquad (2.23)$$

where: N''_L *represents the moist air resonance contributions*

N''_d *represents the dry air nonresonant spectra*

N''_c *is the water vapour continuum spectrum*

N''_w *is the suspended water-droplet-refractivity*

N''_R *is the rain approximation*

Moist air resonance contributions:

Water vapour and oxygen are responsible for the most important contribution to the absorption in the frequency range considered here. In the MPM algorithm the absorption coefficient for water vapour and oxygen are separately calculated for each of the layers in the atmosphere. For one layer N_L"is given by a summation of oxygen resonance contributions at 44 frequencies and water vapour resonance contributions at 30 different frequencies.

$$N_L = \sum_{i=1}^{44} S_i F_i(f) + \sum_{k=1}^{30} S_k F_k(f) \tag{2.24}$$

where: *S is a line strength in kHz.*

$F(f) = F'(f) - jF''(f)$ *is a complex shape function in* GHz^{-1}

The Van Vleck-Weisskopf shape function is used to describe the resonance contributions.
The absorption line spectrum is determined by the imaginary part of $\boldsymbol{F}$:

$$F_i''(f) = \frac{f}{f_i}\left(\frac{\Delta f_i - \delta_i \cdot (f_i + f)}{(f_i - f)^2 + \Delta f_i^2} + \frac{\Delta f_i - \delta_i \cdot (f_i + f)}{(f_i + f)^2 + \Delta f_i^2}\right) \tag{2.25}$$

where the line parameters are:

Oxygen

$\Delta f_i = a_3 \cdot (p \cdot \theta^{(0.8 - a_4)} + 1.1 \cdot e \cdot \theta)$

$\delta_i = (a_5 + a_6 \theta) \cdot 10^{-3} \cdot p \cdot \theta^{0.8}$

$S_i = a_1 \cdot 10^{-6} \cdot p \cdot \theta^{3} \cdot \exp(a_2 (1 - \theta))$

Water vapour

$\Delta f_i = b_3 \cdot (p \cdot \theta^{b_4} + b_5 \cdot e \cdot \theta^{b_6})$

$\delta_i = 0$

$S_i = b_1 \cdot e \cdot \theta^{3.5} \cdot \exp(b_2 (1 - \theta))$

Using the resonance line center frequencies f_i and the so-called spectroscopic parameters $a_{1\text{-}6}$ and $b_{1\text{-}6}$ as given in table 1 in [2] N_L'' can be calculated. From (2.23) together with (2.24) and (2.25) can be seen that the N'' and thus also the attenuation depends on the inverse temperature profile ($\theta(h)$), the pressure profile ($p(h)$) and the partial water vapour pressure profile ($e(h)$).

Dry air non-resonant spectra:

According to Liebe non-resonant refractivity terms of dry air make a small contribution at ground level pressures due to the oxygen below 10 GHz and due to nitrogen above 100 GHz. Calculation of these effects can be found in [2].

Water vapour continuum spectrum:

The continuum absorption N_c'' is said to be determined by series of accurate laboratory measurements, which resulted in the following expression:

$$N_c''(f) = f \cdot (3.57 \cdot \theta^{7.5} \cdot e + 0.113 \cdot p) \cdot 10^{-5} \cdot e \cdot \theta^{3} \tag{2.26}$$

Suspended water droplet refraction:

Suspended water droplets in haze, fog and clouds absorb millimeter-waves considerably. The size of the droplets is below 50μm. According to [2] these droplets give the following contribution:

$$N''_w(f) = \frac{4.5 \cdot w}{\varepsilon'' \cdot (1+\eta^2)} \qquad (2.27)$$

where: *w is the liquid water density profile*

$$\eta = \frac{2+\varepsilon'}{\varepsilon''}$$

ε'' *is the imaginary part of the permittivity for liquid water*

$$\varepsilon''(f) = (\varepsilon_0 - \varepsilon_1) \cdot \frac{f}{f_p} \cdot \left(1 + \left(\frac{f}{f_p}\right)^2\right) + (\varepsilon_1 - \varepsilon_2) \cdot \frac{f}{f_s} \cdot \left(1 + \left(\frac{f}{f_s}\right)^2\right)$$

ε' *is the real part of the permittivity for liquid water*

$$\varepsilon'(f) = \frac{\varepsilon_0 - \varepsilon_1}{1 + \left(\frac{f}{f_p}\right)^2} + \frac{\varepsilon_1 - \varepsilon_2}{1 + \left(\frac{f}{f_s}\right)^2} + \varepsilon_2$$

$\varepsilon_0 = 77.66 + 103.3 \cdot (\theta - 1)$

$\varepsilon_1 = 5.48$

$\varepsilon_2 = 3.51$

$f_p = 20.09 - 142 \cdot (\theta - 1) + 294 \cdot (\theta - 1)^2$

$f_s = 590 - 1500 \cdot (\theta - 1)$

Rain approximation:

Refractivity of rain is mainly caused by absorption and scattering. The effect becomes substantial when radio wavelength and drop diameters (0.1 to 5 mm) are in the same range. In [2] Liebe shows how the rain contribution can be calculated. Because the interest in the case of the radiometer measurements is to clouds, periods of rain are not taken into account. Therefore absorption by rain is not further mentioned here.

2.2.3 Parameters derived from the refractivity

Having determined all separate contributions the imaginary part of the complex dispersive refractivity, $N''(f)$, can be used to calculate the absorption coefficient α:

$$\alpha_{dB} = 0.1820 \cdot 10^{-3} \cdot f \cdot N''(f) \qquad \text{[dB/m]} \qquad (2.28)$$

with: *f the frequency in GHz.*

Integrating over the total number of layers in the atmosphere results in the total attenuation A [dB] that can de written as:

$$A_{dB} = \int_0^L \alpha_{dB}(h')dh' \qquad \text{[dB]} \qquad (2.29)$$

where: *h is a path through the atmosphere [m]*

A quantity that is often used to express the attenuation is the *optical thickness* or *opacity* (τ) which is nothing more than the attenuation in Neper:

$$\tau = 0.23025 \cdot A_{dB} \qquad [\text{Np}] \qquad (2.30)$$

For the reason that the radiometer measures brightness temperatures it may be necessary to calculate T_b for the test frequencies from the atmospheric profiles. For this the following relation between attenuation and brightness temperature T_b is used:

$$A_{dB} = 10 \cdot \log \frac{T_{eff} - T_{bg}}{T_{eff} - T_b} \quad [\text{dB}] \qquad \tau = \ln \frac{T_{eff} - T_{bg}}{T_{eff} - T_b} \quad [\text{Np}] \qquad (2.31)$$

where: T_{eff} *is the effective temperature in K*
T_{bg} *is the cosmic background temperature in K*

The effective temperature T_{eff} is defined as:

$$T_{eff} = \frac{\int_0^L T(h)\alpha(h)\exp(-\tau_{(0,h)})dh}{1 - \exp(-\tau_{(0,h)})} \qquad (2.32)$$

Usually an estimated value for T_{eff} is determined, based on climatological parameters, which is used in further calculations.

So it can be concluded that MPM can be used to obtain attenuation, brightness temperatures, water vapour and liquid water concentrations from atmospheric profiles.

3. *Water retrieval algorithms*

There are different kinds of algorithms to retrieve liquid water and water vapour contents of the atmosphere from the measured brightness temperatures. The most simple algorithms assume the attenuation (A) to be a linear combination of V and L. From this assumption it can be concluded that V and L can be expressed as a linear combination of the attenuation at 2 different frequencies. There are 3 different *linear algorithms* described in this section: CCIR, SIGMA A and SIGMA B.

Another category of algorithms tries to match profiles of a modelled atmosphere to the profiles of the real atmosphere. This is done in such a way that the brightness temperatures calculated from this 'matched' atmosphere agree with the measured values. Generating the set of modelled atmospheres is done on basis of the ground level values of temperature, pressure and relative humidity. By using the cloud base height and a relative humidity reference level as tuning parameters, the brightness temperatures calculated from the modelled atmosphere are made to agree with the measured values. This kind of algorithms are named *Matched Atmosphere Algorithms*.

For the periods when data from radiosondes are available, temperature, pressure and relative humidity profiles are known. From these profiles the amount of water vapour in the atmosphere can be calculated directly. When information about the height of cloud base and cloud top is derived from radar or lidar measurements, a cloud can be introduced in the liquid water density profile according to (2.19). The only tuning parameter left is C indicating the cloud type. When the best match between the measured brightness temperatures is found, the amount of liquid water is calculated from the corresponding profiles.

For the periods when radiosonde data are available this method can be used to get a certain reference to check the accuracy of the other algorithms. During the measurement campaign 3 or 4 radiosondes were launched each day.

In this section the different algorithms are described and in Chapter 5 the results are compared.

3.1 *Linear algorithms*

Linear algorithms are based on the property that in situations where there is no rain, atmospheric attenuation is mainly caused by absorption by gas molecules (water vapour and oxygen) and by water droplets in clouds and fog. This means that the attenuation at a certain frequency (and thereby the observed sky noise temperature) depends strongly on V and L. When the sky noise is measured simultaneously at 2 different frequencies it is possible to determine V and L. The linear algorithms described in this section are the CCIR model based on CCIR report 719 and the SIGMA A and SIGMA B models developed by Sigma Consultants (Sweden) based on a large number of radiosonde observations from several sites in Europe [4]. The CCIR algorithm is implemented in the measurement software of the RESCOM radiometer to display real-time values of integrated water vapour and liquid

water on the screen. All 3 linear algorithms are described in the Rescom 20/30 Radiometer user manual [6], More details about the SIGMA algorithms are given in [4].
In all these algorithms the following parameters are set to the values as used in the actual measurements:

f_1=21.3GHz

f_2=31.7GHz

φ=90° *(antenna elevation angle)*

It must be remarked that the brightness temperature in the 20GHz range (21.3GHz in our case) is often referred to as T_{20} throughout this report, whereas for the brightness temperature in the 30GHz range (31.7GHz in our case) this is T_{30}.

3.1.1 CCIR model

The CCIR model assumes that there is a linear relationship between the total attenuation A_{dB} at a given frequency f and the integrated water vapour content (V) liquid water content (L) and the attenuation by other gasses. Hence V and L can be determined by solving a pair of equations of the form:

$$A(f)=a(f)\cdot V+b(f)\cdot L+c(f,h_0) \quad \text{[dB]} \tag{3.1}$$

where: *a is the specific attenuation due to water vapour*
b is the specific attenuation due to liquid water
c is the total attenuation due to dry-air (mainly oxygen)
h_0 is the height of the test site above sea level

Recalling that $\tau = 0.23025 \cdot A_{dB}$ (2.30) using Equation 3.1, V and L can be expressed explicitly in terms of optical thickness, which leads to the algorithm as it is actually implemented:

$$V = d_o(d_1 \cdot \tau(f_1) - \tau(f_2) - d_2) \tag{3.2}$$

and

$$L = d_o'(d_1' \cdot \tau(f_1) - \tau(f_2) - d_2') \tag{3.3}$$

where: *$\tau(f_1)$ is the opacity at frequency f_1=21.3GHz*
$\tau(f_2)$ is the opacity at frequency f_2=31.7GHz

Since the brightness temperatures at 21.3 GHz and 31.7 GHz are measured by the radiometer, both opacities can be calculated using Equation 2.31. The effective temperature used in the CCIR algorithm is:

$$T_{eff}(f) = a_1(f) \cdot (1 - a_2(f)) \cdot T_{CCIR} \tag{3.4}$$

where: T_{CCIR}=288.15K

CCIR report 719 shows how the constants $d_0, d_1, d_2, d_0', d_1'$ and d_2' can be calculated from the specific attenuations of water vapour, liquid water and oxygen. These parameters are based on long-term meteorological data from radiosondes and therefore depend on the geographical location of the test site. In Appendix A a table with values of the parameters used in the CCIR algorithm for both northern as southern part of Europe is given.

3.1.2 SIGMA models

In the Sigma models it is assumed that there is a linear relation between the amount of water vapour and a *'liquid invariant parameter'* X. This parameter X is a function of opacity τ which on its turn follows from the brightness temperature using (2.31).

In the Sigma models the effective temperature is calculated in the same way a done in the CCIR algorithm, Equation 3.4.

The liquid invariant parameter can be found by writing the opacities at frequencies $f_1 = 21.3\ GHz$ and $f_2 = 31.7\ GHz$ as a sum of separate absorption coefficients:

$$\tau_{f1} = \int_0^\infty (\alpha_{V,f1} + \alpha_{Ox,f1} + \alpha_{L,f1}) \cdot dx \qquad \text{[Np]} \qquad (3.5)$$

$$\tau_{f2} = \int_0^\infty (\alpha_{V,f2} + \alpha_{Ox,f2} + \alpha_{L,f2}) \cdot dx \qquad \text{[Np]} \qquad (3.6)$$

where: α_V *is the absorption coefficient due to water vapour in Np*
α_{Ox} *is the absorption coefficient due to oxygen in Np*
α_L *is the absorption coefficient due to liquid water in Np*

Note that so far the formulation is entirely equal to the CCIR algorithm.

According to [4] it can be assumed that the attenuation coefficient for liquid water is proportional to the square of the frequency. This assumption is said to be valid as long as the size of the water drops is much smaller than the observed wavelength, which in this case is approximately 1 cm. This relation between $\alpha_{L,f1}$ and $\alpha_{L,f2}$ can be written as:

$$\alpha_{L,f2} = \left(\frac{f_2}{f_1}\right)^2 \cdot \alpha_{L,f1} \qquad (3.7)$$

So by multiplying (3.5) by $(f_2/f_1)^2$ and subtracting (3.6) the liquid invariant parameter is obtained:

$$X = \left(\frac{f_2}{f_1}\right)^2 \cdot \tau_{V,f_1} - \tau_{V,f_2} - \tau_{Ox} \qquad (3.8)$$

where: $\tau_{Ox} = \int_0^\infty \left(\left(\frac{f_2}{f_1}\right)^2 \alpha_{Ox,f_1} - \alpha_{Ox,f_2}\right) ds$

This τ_{Ox} can be estimated using observations of ground temperature and ground pressure as shown in [4] and [6]:

$$\tau_{Ox}(f) = \tau_{Ox}(19) \cdot \left(2.2229 - 2.715 \cdot \frac{f}{19} + 1.486\left(\frac{f}{19}\right)^2\right) \qquad (3.9)$$

where: $\tau_{Ox}(19) = 0.0154 \cdot \left(P_0^2 \cdot (T_0 - 21)^{-2.4} \cdot (0.012 + 0.00173 \cdot (T_0 - 21)\right)$

3.1.2.1 SIGMA-A model

The SIGMA-A algorithm uses the liquid invariant parameter and additional ground data to calculate the integrated water vapour content. The algorithm for water vapour retrieval has the form:

$$V = c_{eff}\left[1 + a_{V1}\cdot(P_0 - \overline{P}_0) + a_{V2}\cdot(T_0 - \overline{T}_0) + a_{V3}\cdot(X - \overline{X})\right]\cdot X \qquad (3.10)$$

where: $\overline{X}$ *is the mean value of the liquid invariant parameter X*

$\overline{P}_0$ *is the observed mean value for the ambient pressure at ground level*

$\overline{T}_0$ *is the observed mean value for the ambient temperature at ground level*

P_0 *is the actual air pressure at ground level*

T_0 *is the actual temperature at ground level*

The constants c_{eff}, a_{V1}, a_{V2} and a_{V3} are given in Appendix A.

The algorithm for calculating the liquid water content is as follows:

$$L = a_{L0} + a_{L1}P_0 + a_{L2}T_0 + a_{L3}\tau_{f_1} + a_{L4}\tau_{f_2} \qquad (3.11)$$

where a_{L0}, ..., a_{L4} *are given in Appendix A.*

3.1.2.2 SIGMA-B model

This model can be used when no real-time meteorological data are available. The known annual periodicity of the meteorological factors is used with the intention to obtain a better retrieval accuracy. This leads to the following algorithm:

$$V = c_{eff}\left[1 + b_{V1}\cdot\sin\left(\tfrac{2\pi t}{365}\right) + b_{V2}\cdot\cos\left(\tfrac{2\pi t}{365}\right) + b_{V3}\cdot(X - \overline{X}) + b_{V4}\cdot h_0\right]\cdot X \qquad (3.12)$$

where: *X is the liquid invariant parameter as described in 3.1.2.1*
t is the number of the day in the year
h_0 *is the height of the test site above sea level in m*

$$L = b_{L0} + b_{L1}\cdot\sin\left(\tfrac{2\pi t}{365}\right) + b_{L2}\cdot\cos\left(\tfrac{2\pi t}{365}\right) + b_{L3}\cdot\tau_{f_1} + b_{L4}\cdot\tau_{f_2} + b_{L5}\cdot h_0 \qquad (3.13)$$

Also for this algorithm sets of coefficients (b_{V1}, ... , b_{V4} , c_{eff} , and b_{L1}, ... , b_{L5}) are given in Appendix A.

3.2 Matched Atmosphere Algorithm

As was shown in Section 2.2, MPM needs information about the atmosphere (i.e. temperature, pressure and relative humidity profiles) to calculate brightness temperatures and attenuation. Usually these profiles are only available at times when a radiosonde is launched. When, however, no radiosonde data are available, an estimation of the atmosphere characteristics has to be made.

The Matched Atmosphere Algorithm makes an estimation of the atmosphere, based on ground level meteorological measurements, using CCIR standard profiles in which cloud base height and relative humidity reference level are used as tuning parameters. MPM is used here to calculate the brightness temperatures from this modelled atmosphere. When these calculated brightness temperatures correspond to the measured values as closely as possible the atmosphere is said to be matched and V and L are determined.

The most essential step in the Matched Atmosphere Algorithm is the estimation of the temperature, pressure and relative humidity profiles to be used in the calculations. The estimations of these parameters can be done with the use of several assumptions. The Matched Atmosphere Algorithm, as we name it, is based on the 'profile algorithm' developed by Peter and Kämpfer [7]. In this algorithm Peter and Kämpfer use a model in which the troposphere is divided in horizontal layers of a certain thickness (100 m in our calculations). Each of these layers is taken to be homogeneous. The brightness temperatures can now be calculated using MPM by evaluating the contributions of all separate layers and adding them all up. Each layer is characterised by its temperature, relative humidity and pressure. In the atmosphere model the following profiles are used:

Temperature profile T(h)

The temperature profile $T(h)$ matches the measured ground value and approaches the local initial temperature profile $T_{init}(h)$ for greater heights. The initial temperature profile is site specific and can be determined from meteorological data or a standard atmosphere can be used.
If the CCIR standard atmosphere is applied, the temperature is approximated with a piece-wise linear function. Up to a height of 12 km T_{init} is determined by the adiabatic lapse rate of -6.5 K/km. This leads to the following expression for the temperature profile

$$T(h) = T_{init}(h) + \left(T(h_0) - T_{init}(h_0)\right) \cdot \exp\left(\tfrac{-h}{3}\right) \qquad \text{[K]} \qquad (3.14)$$

where: *h height in km (h<12km)*
h_o is ground level
$T_{init}=T_0-6.5h$ [K]
T_0 is the CCIR standard ground temperature, 288.15K

The temperature profile in degrees Celsius is shown in Figure 3.1.

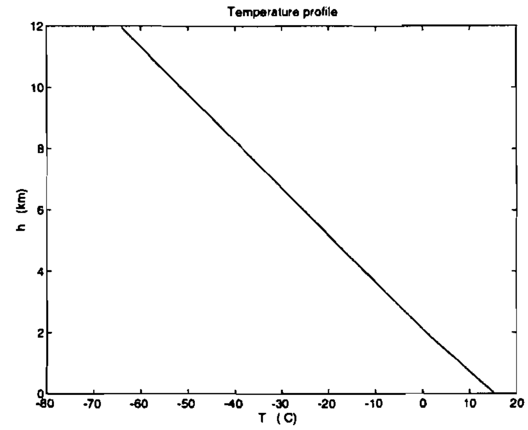


Figure 3.1 CCIR Temperature profile

Pressure profile P(h)

The pressure profile *P(h)* is not a critical parameter in the calculations. It can be approximated by a standard exponential profile which matches the pressure at ground level.

$$P(h) = P(h_0)\cdot\left(\frac{T_0}{T_0 - 6.5h}\right)^{\frac{34.163}{-6.5}} \qquad \text{[kPa]} \qquad (3.15)$$

where: $P(h_0)$ *is the pressure at ground level in kPa ; (* $P(h_0)$ *= 101.325 kPa under CCIR conditions)*

This pressure profile is illustrated in Figure 3.2.

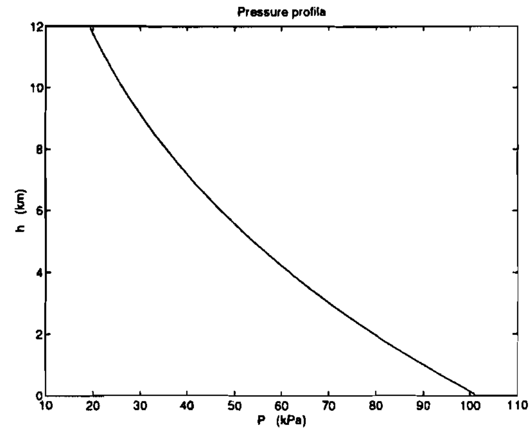


Figure 3.2 CCIR pressure profile

Relative humidity profile RH(h)

In the atmosphere model of Peter and Kämpfer [7] the relative humidity profile is approximated with a piece-wise linear function, which is quite a simplification of reality. This approximation is based on a number of assumptions.

- *RH(0) is the relative humidity at ground level, which is measured;*
- *RH(h) at a height of 12 km and more is negligible and therefore set to 0%;*
- *RH(h) is assumed to be 100% in a cloud;*
- *RH(h) is expected to be constant (with value of* RH_{ref}*) from 1.5 km above ground level to the base of the cloud,* H_{base}*, and from the top of the cloud to 1.5 km above that point. (When there is no cloud* $H_{base}=H_{top}$*).*

This results in the profile as is shown in Figure 3.3

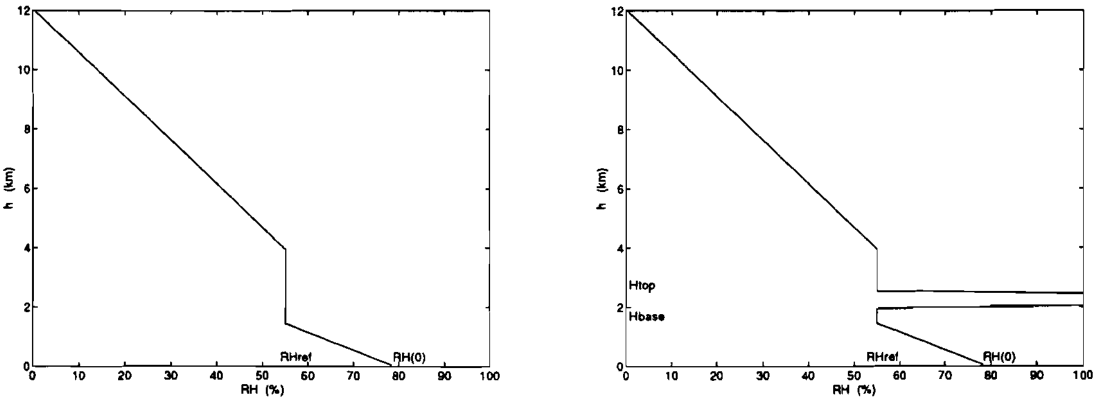


Figure 3.3 Relative humidity profiles

Having established profiles for all input quantities, there are a number of parameters (RH_{ref}, H_{base}, H_{top} and the cloud type parameter C as introduced in Equation 2.19) which can be varied within a certain range. The Matched Atmosphere Algorithm tries to determine these parameters so that the brightness temperatures calculated from the obtained profiles (using MPM) match the measured values as close as possible.

More about the software implementation and the working of the Matched Atmosphere Algorithm will be described in the next chapter.

3.3 Using measurement data from other instruments

In the previous section it was said that the Matched Atmosphere Algorithm makes an estimation of the atmosphere based on ground level meteorological data and tuning parameters, in order to determine the integrated water vapour and liquid water content. When, however, additional information obtained from other measurement instruments is available and introduced in the algorithm, a better estimation of the atmospheric profiles can be made, which would result in a more accurate retrieval of V and L.

In the so called 'Awater' project there is a co-operation between the Technical Universities of Eindhoven and Delft in research efforts to find a way to measure the concentrations and profiles of liquid water and water vapour in the atmosphere. This research project is closely associated to another project called 'CLARA' (Clouds and Radiation) in which several institutes work together in a number of measurement campaigns (each of about 2 weeks), monitoring the atmosphere with different instruments. The data obtained in this way offer the unique possibility to gain insight in the accuracy of atmosphere models, algorithms to determine V and L and other information about clouds.

The institutes contributing to this project are the following:

- TU-Delft:

  Radar: measuring reflection coefficients from which height, concentration and velocity of water droplets can be determined. At first this leads to information about height of the base and the top of the cloud. In a later stage also water concentrations can be obtained from these measurement data.

- TU-Eindhoven:

  20/30 GHz Radiometer: measuring sky brightness temperatures and determining V and L and also an indication of the height of the clouds.

- KNMI:

  - Radiosondes: measuring temperature, pressure and relative humidity profiles of the atmosphere,
  - Ground measured meteorological data (T, P, RH),
  - Lidar: measuring the base height of clouds.

- RIVM:

  Lidar: measuring the base height of clouds.

- ECN:

  FSSP: determining a water droplet distribution (number and size) when flying through the clouds.

- FEL-TNO:

  Infrared radiometer

In the next chapter it is described how data from these instruments can be used in the Matched Atmosphere Algorithm with the objective to gain more insight in the accuracy of the results.

4. Software implementation

This chapter describes the implementation of the different algorithms for the retrieval of integrated water vapour and liquid water amounts in the atmosphere from brightness temperatures measured with a radiometer. In our case we use the measured brightness temperature values at 21.3GHz and 31.7GHz averaged over 1 minute.

The software was developed using MATLAB for windows.

4.1 Linear algorithms

The implementation of the linear algorithms, CCIR, SIGMA-A and SIGMA-B, is very straightforward. It consists of the formulas as given in Sections 3.1.1 and 3.1.2. The coefficients used in these equations are given in Appendix A. In the present implementation of the algorithms the coefficients for the northern part of Europe have been used.

4.2 The Matched Atmosphere Algorithm

As was remarked in Section 3.2 the essence of the Matched Atmosphere algorithm is, to tune the parameters RH_{ref}, H_{base}, H_{top} and C, in such way that the brightness temperatures calculated from the modelled atmosphere agree with the measured values.

In [8] H.J. Hollander showed that the Matched Atmosphere Algorithm can be implemented in different ways. One possibility is to tune the parameters with an iterative method. In [9] H.W.H. de Groot demonstrated that this way of calculating V and L is not suitable for real-time calculations because of the lack of processing speed. Another implementation described in [8] uses linear interpolation to calculate V and L from a beforehand determined look up table. This implementation was called MALU and is the basis of the Matched Atmosphere Algorithm as it is implemented at the moment. Till then the Matched Atmosphere Algorithm had only been used to calculate integrated water vapour and liquid water amounts for single observation points. Within the CLARA project, however, it was desirable to carry out calculations for all measurement point of a whole day and processing speed was therefore of more importance. In this report only the implementation of the look up method (MALU) is applied, in all cases where the Matched Atmosphere Algorithm is mentioned this method is meant. In this section the working of the look up method of the Matched Atmosphere Algorithm is explained, and changes compared to the original implementation are clarified.

When the atmosphere is modelled with the temperature, pressure and relative humidity profiles as shown in Section 3.2, there are a number of variables left to be tuned, namely:

- RH_{ref} : the relative humidity reference level
- H_{base} : the cloud base height
- H_{top} : the cloud top height
- C : the parameter depending on the cloud type.

In the original form of the Matched Atmosphere Algorithm it is assumed that only ground level data of *T, P* and *RH* are available. The objective is, to use two of the above mentioned variables as tuning parameters and find a fixed expression for the other two. This way a set of (T_{20}, T_{30}, V, L) combinations is obtained from which unique values for the amount of water vapour and liquid water can be determined. In the original implementation no information about cloud height obtained from lidar or radar measurements is applied. Since Peter and Kämpfer made assumptions on the height of the cloud top, these are used to appoint H_{top}. According to [7] the top of the cloud is determined by the level where the droplets begin to freeze. Above this level there is no water in vaporised or liquid form and the ice crystals that are present do not contribute significantly to the microwave absorption in the range of 20 to 30 GHz. The temperature at which ice crystals growth begins can vary from -3°C to -10°C depending on the cloud type, ice nuclei and geographical location. For simplicity Peter and Kämpfer took the altitude of the 0°C level as H_{top}. The cloud top is determined from the temperature profile as expressed in Equation 3.14 and therefore depends on the temperature at ground level. To prevent unrealistic low or even negative cloud top height to occur, due to low ground level temperatures, it is necessary to set a minimum value for H_{top}. In the Matched Atmosphere Algorithm, as it is implemented at the moment, a minimum height of the cloud top is set to 2 km.

Having appointed H_{top} there are 3 possible tuning parameters left. In [8] H.J. Hollander showed that the retrieval of V and L is much more sensitive to changes in RH_{ref} and H_{base} than to changes in C (Same was confirmed in [9]). This is the reason for using RH_{ref} and H_{base} as tuning parameters and putting C at a fixed value. According to [7] C may vary within the range of 0.1 to 0.75. In the Matched Atmosphere Algorithm C set to 0.4 (a value in the middle of its possible range).

Now we have 2 variables left to characterise the atmosphere; the reference humidity RH_{ref} determining the amount of water vapour and the cloud base altitude H_{base} indicating the cloud thickness. Now, for each combination of ground level temperature, pressure and relative humidity all possible atmospheres can be constructed by varying RH_{ref} and H_{base} over there full range. For RH_{ref} this range is from 0% till 100% in steps of 20%, for H_{base} this is from 100m above ground level to H_{top} in steps of 100m. From all atmosphere constructed this way, the brightness temperatures at 21.3GHz and 31.7GHz can be calculated using Liebes MPM. Now the atmospheric profiles are fixed, also the V and L values corresponding to the atmospheres can be determined as shown in Section 2.2. When all these T_{20}, T_{30} combinations are stored together with the corresponding V and L values a look up table is obtained. This look up table contains all combinations of T_{20} and T_{30} that, according to the atmosphere model, can be realised with the particular ground level values of *T, P* and *RH*; the so-called *convergence area*. The look up table for V and L and convergence area, corresponding to ground level values $T(0)=15°C$, $P(0)=101.3kPa$ and $RH(0)=60\%$ *(CCIR standard ground level condition)*, is illustrated in Figure 4.1.

It can be seen that the amount of water vapour and liquid water are a function of the brightness temperatures defined with the convergence area as domain. In the version of the Matched Atmosphere Algorithm as implemented by H. Hollander (MALU) the standard two dimensional interpolation routines of MATLAB are used for the retrieval of V and L. To be able to use these routines a matrix of samples describing the two dimensional functions are needed. The indices of the matrix elements are the brightness temperatures T_{20} and T_{30}. Thus, when the range of both T_{20} and T_{30} is chosen to be 1K to 100K this leads to a 100×100 matrix with as matrix elements the V and L values corresponding to the particular brightness temperature combinations. The matrix elements $V(T_{20},T_{30})$ and $L(T_{20},T_{30})$ are calculated from the look up table using linear interpolation when inside the convergence area and linear extrapolation when outside the convergence area. These 100×100 matrices will be called *interpolation sets* from now on.

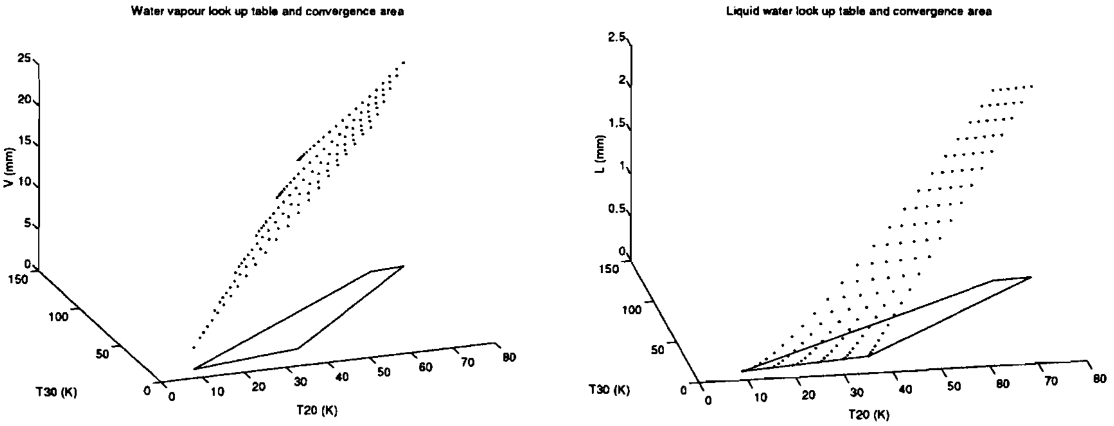


Figure 4.1 Look up table for water vapour and liquid water with the corresponding convergence area
T(0)=15°C, P(0)=101.3kPa, RH(0)=60%

When MALU is used to calculate the integrated water vapour and liquid water with the measured brightness temperatures, this is done by choosing the right interpolation set, corresponding to the actual ground level meteorological values, and determining *V* and *L* from this set by bi-linear interpolation. The creation of one interpolation set takes about 20 minutes on a Pentium 90 computer, which makes on-line processing of radiometer measurement impossible.

When the interpolation set is available, a look up action can be carried out within 5ms. For on-line data processing the interpolation sets for all possible ground level data combinations have to be calculated beforehand and stored on a hard-disk. One interpolation set takes 161 kbytes of disk space. In [9] it is suggested that for covering the complete range of ground meteorological variables values (temperature from -30 to 30 degrees in steps of 1 degree, pressure from 997 to 103 kPa in steps of 1kPa and relative humidity from 0 to 100% in steps of 10%) a total number of 3960 interpolation sets would be necessary, using 637 Mbyte of disk space. Calculating all these interpolation sets would take about 1320 hours, which is about 55 days. When only the interpolation sets are created for those combinations of ground level meteorological values that are realistic, this may reduce the number of needed sets by half. This means that still about 27 days are needed to calculate the necessary interpolation sets.

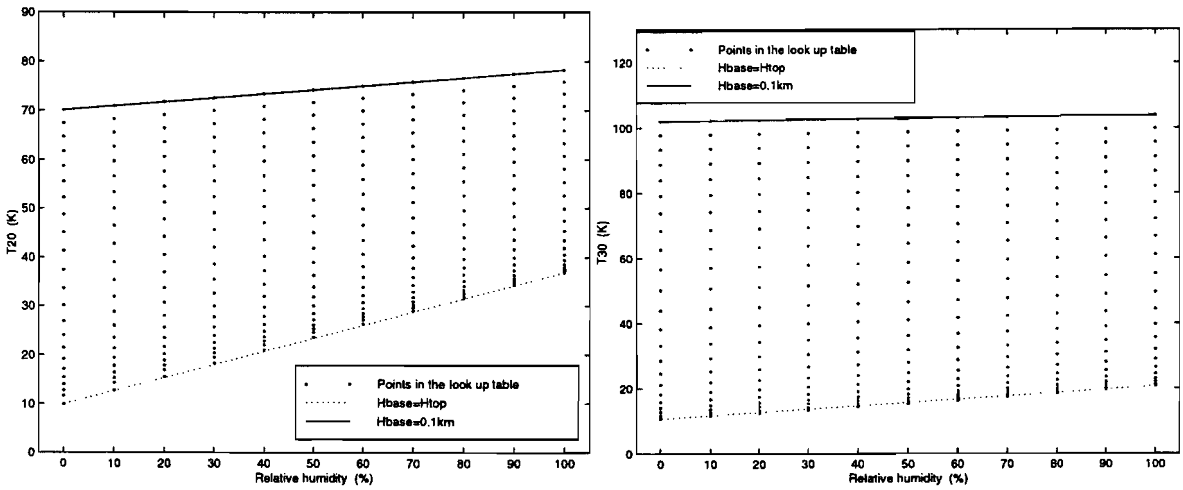
The implementation of the Matched Atmosphere Algorithm as suggested by H. Hollander leads to practical problems due to lack of calculation speed and disk space. Therefore I have been looking for manners to speed up the calculations needed to construct the interpolation sets and ways to limit the amount of disk space needed.

In the construction of the interpolation sets there are 2 steps that take much time, namely:

- the calculation of the brightness temperatures from the modelled atmospheres using the MPM,
- the construction of the interpolation set from the look up table.

In order to speed up the process a closer look has been taken at the construction of the look up table with the objective to see if the number of brightness temperatures calculations can be reduced. In the original implementation the brightness temperatures at 21.3GHz and 31.7GHz both are calculated for all values of RH_{ref} and H_{base} . This means that when $H_{top}=2km$ the number brightness temperature calculations is $2 \cdot 11 \cdot 20=440$, which takes about 4 minutes on a Pentium 90 computer.

When the water vapour values of the look up table are plotted as a function of RH_{ref} this leads to the graph as depicted in Figure 4.2(a). Figure 4.2(b), (c) and (d) show the same for T_{30}, V and L . The variable H_{base} is a parameter in these graphs. From Figure 4.2 (a), (b) and (c), can be seen that, for each fixed value of H_{base} , both T_{20}, T_{30} as well as V increase linear with RH_{ref}. This means that the brightness temperatures and water vapour values only have to be calculated for the points in the look up table that correspond to $RH_{ref}=0\%$ in combination with all values of H_{base} and $RH_{ref}=100\%$ in combination with all values of H_{base}. All intermediate points can be found by means of linear interpolation, which can be carried out considerably faster then calculating each individual point in the look up table using the MPM.



(a) T_{20} as function of RH_{ref} *(b) T_{30} as a function of RH_{ref}*

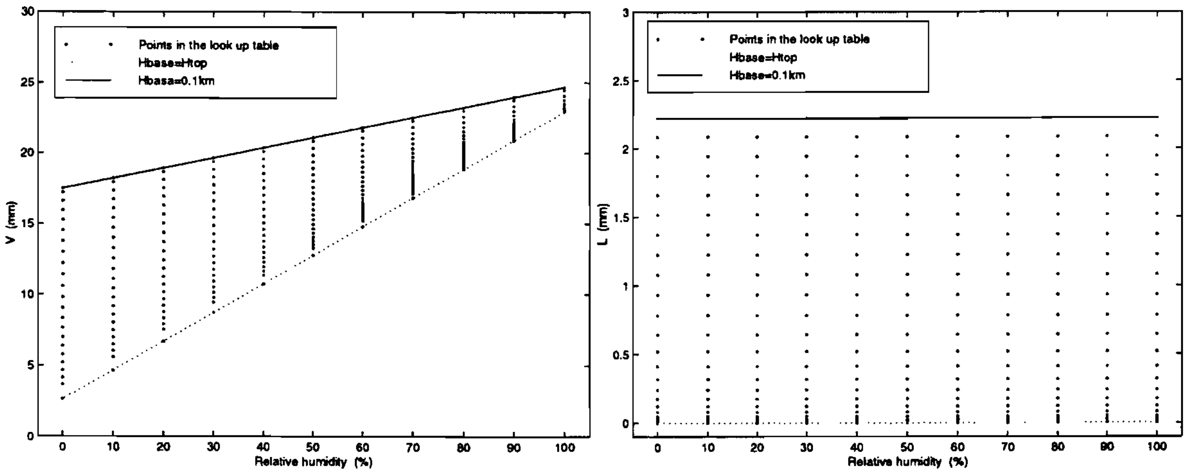


Figure 4.2 (c) V as function of RH_{ref} *(d) L as a function of RH_{ref}*

From Figure 4.2(d) can be seen that the amount of liquid water does not depend on the tuning parameter RH_{ref} but only on the thickness of the cloud and thus H_{base}. Therefore also for the amount of liquid water values only have to be calculated for the points in the look up table that correspond to $RH_{ref}=0\%$ in combination with all values of H_{base} and $RH_{ref}=100\%$ in combination with all values of H_{base}. and the intermediate points can be found by means of linear interpolation.

Constructing the look up table in the way as previously mentioned reduces the calculation time considerably. Generating the look up table can now be carried out within 53 seconds on a Pentium 90 computer, where in the original way this took about 4 minutes.

Another point in the original implementation of the Matched Atmosphere Algorithm (MALU) that takes much calculation time is the construction of the 100×100 matrix that is used as interpolation set, as was described in Section 4.2. This step becomes superfluous when for the measured brightness temperature combination the corresponding V and L values are directly calculated from the look up table. This can be done when not the standard MATLAB routines but a special interpolation procedure is used for the calculations. In this new procedures, which was implemented, the values for V and L are calculated from the three nearest points in the look up table, which are not on a straight line, by linear interpolation in two dimensions. When the measured brightness temperature combination is outside the convergence area V and L are calculated by linear extrapolation in two dimensions. Interpolating from the three nearest point may be risky when these points are nearly on a straight line. When this is the case considerable errors can be made. When, however, the measurement points are within the convergence area the three nearest points always form a useful basis for the interpolation. Only when the measurement points are far outside of the convergence area the interpolation results become inaccurate.

Applying the before mentioned routine makes the construction of the 100×100 matrix superfluous and this way saves 16 minutes of computing time. In total the time needed to construct a interpolation set is reduced from 20 minutes to about 53 sec.

Another point in which the look up table has changed is that, besides the brightness temperatures, V and L also the corresponding values of RH_{ref}, H_{base} and H_{top} are stored. This makes it possible not only to calculate V and L with the measured brightness temperatures, but also to reconstruct a modelled atmosphere that resulted in these values. This way an idea about the cloud height, estimated by the Matched Atmosphere Algorithm, can be determined. Because of the fact that V, L, RH_{ref}, H_{base} and H_{top} are interpolated separately the modelled atmosphere can not be reconstructed exactly, but a fairly good impression can be obtained. Storing all information takes about 30 kbyte per look up table. Storing the at least 3960 look up tables needed for real-time data processing with the Matched Atmosphere Algorithm in this case will take about 120Mbyte. It can be concluded that this implementation is a considerable improvement in both processing speed and reduction of required disk space.

For the processing of the measurement data of the CLARA campaigns it has been chosen not to make use of stored look up tables. In the present implementation the Matched Atmosphere Algorithm reads the input values of the measured brightness temperatures together with the actual ground level values of temperature, relative humidity and optionally pressure (till now the pressure has been set to a fixed value of 101.3kPa because the actual pressure was not always available and, as will be shown later, the influence of pressure changes on the result is small). With the set of ground level variables corresponding to the first measurement point, an initial look up table is calculated. This look up table is applied until the change in one of the ground level values (compared to the initial situation) is more than a beforehand determined threshold. Whenever one of these thresholds is exceeded a new look up table is calculated, which will be applied from then on. Presently a new look up table is going to be used when ever there is a change of 2 degrees in temperature or 10% in relative humidity. If this is a reasonable choice will be discussed later. With the current implementation processing of the 1440 measurement points (averages over 1 minute) of 1 day takes about 10 to 15 minutes on a Pentium 90 computer.

Finally some remarks have to be made about the convergence area. As was said before, the convergence area is the set of all possible combinations of T_{20} and T_{30} that can be obtained from all atmospheres corresponding to particular ground level variables, when H_{base} and RH_{ref} are varied over there full range. In the real implementation of the Matched Atmosphere Algorithm the convergence area is defined by the area in-between the 4 corner points which correspond to the following RH_{ref}, H_{base} combinations: $(RH_{ref}=0\%, H_{base}=0.1)$, $(RH_{ref}=0\%, H_{base}=H_{top})$, $(RH_{ref}=100\%, H_{base}=H_{top})$, $(RH_{ref}=100\%, H_{base}=0.1)$. In Figure 4.3 shows the convergence area corresponding to $T(0)=15°C$, $P(0)=101.3kPa$ and $RH(0)=60\%$ together with all combinations of T_{20} and T_{30} that are part of the look up table. From this figure can be seen that defining the convergence area by the 4 corner points results in an area that slightly differs from the area that is found when the exact contours are used. Determining the exact contours of the convergence area would introduce extra complexity in the algorithm, where the definition with the 4 corner points serves the purposes sufficiently.

To determine if a combination of measured brightness temperatures is part of the convergence area, it is checked if the point is underneath the lines 2 and 3 and above the lines 1 and 4. This is done by deriving the equations of the 4 lines and filling in the values of the measurement point. When the measurement point is outside of the convergence area the values of V and L are calculated by linear extrapolation. This may however lead to unrealistic results. As will be shown later negative amounts of water liquid can be obtained this way, which is of course physically impossible. The reason for the unrealistic results is that it is not possible to generate a model atmosphere with brightness temperatures that are equal to the measured values. When for brightness temperature combinations out side of the convergence area the atmosphere is reconstructed according to the RH_{ref} and H_{base} values as stored in the look up table, this leads to unrealistic situation such as H_{base} that is negative or higher than H_{top} or RH_{ref} values that are less than 0% or more 100%. Therefore reconstructing the model atmosphere for points outside of the convergence area does not make much sense.

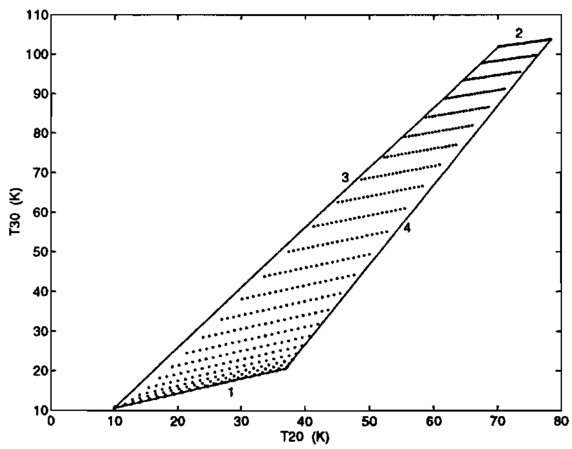


Figure 4.3 The convergence area corresponding to $T(0)=15°C$, $P(0)=101.3kPa$ and $RH(0)=60\%$ with all points in the look up table

4.3 Adaptive linear algorithm

In Section 4.2 it has been shown that for storing the look up tables, needed for real time data processing with the Matched Atmosphere Algorithm, a minimum amount of disk-space of about 120Mbyte is necessary. When the amount of disk-space is limited and one still would desire real-time processing of the measurement data this would call for another strategy. The objective is to approximate the look up tables used in for water vapour and liquid water retrieval in the Matched Atmosphere Algorithm with a flat plane. This way a linear algorithm is obtained in which the parameters depend on the ground level meteorological values.

When we look at the look up tables for V and L in Figure 4.1, it can be seen that both planes have a rather smooth character. For both water vapour and liquid water a linear approximation can be made using the least square method. When for instance for the case of the look up tables of Figure 4.1 a best fitting plane is determined for both V and L, this leads to the following equations:

$$V = 0.934 \cdot T_{20} - 0.444 \cdot T_{30} - 2.161 \qquad \text{[mm]} \qquad (4.1)$$

and

$$L = -0.010 \cdot T_{20} + 0.031 \cdot T_{30} - 0.2930 \qquad \text{[mm]} \qquad (4.2)$$

The largest deviation between the points in the look up table and the corresponding value calculated with this approximation for V is 0.534mm and for L this is 0.1mm. Linear approximation of the amount of water vapour does introduce maximum errors of about 10%, which is acceptable. Linear approximation of the liquid water contents introduces errors that are in some cases in the same order of magnitude as the L values themselves and therefore does not seem very successful. Still it has been chosen to implement the method in which the look up tables are approximated by a flat plane, to see what the differences are when results are compared to those obtained with the linear algorithms (CCIR, SIGMA-A and SIGMA-B) and the regular implementation of the Matched Atmosphere Algorithm.

The implementation of this *'adaptive linear algorithm'* is done by calculating all separate look up tables for all combinations of ground level meteorological variables and finding the best fitting planes for V and L in terms of least squares. In the present implementation this is done for all temperatures in the range of -30°C to 30°C in steps of 1°, relative humidity in the range of 0% to 100% in steps of 5%, the pressure is set to a fixed value of 101.3kPa for now, but has to be varied in a later stage too. (As will be shown later the ground pressure level has very little effect on the results of the V and L retrieval. The actual ground level pressure levels for the CLARA campaign were not available at first, therefore this variable has not yet been included in the calculations yet). The coefficients in the equations of the planes found by approximation are stored in a file. To characterise one look up table by its coefficients, 72bytes are needed. For the total algorithm about 275kbyte would be required, which is considerably less then the 120Mbyte needed when all look up tables are stored completely.

To calculate the values for V and L with a measured brightness temperature combination, the coefficients corresponding to the actual ground level meteorological values are picked from the stored table. These coefficients give the equations to calculate the values for V and L.

The different algorithms described in this chapter were used to calculate the integrated amount of water vapour and liquid water vapour for the first two CLARA measurement campaigns. The results of these calculations are shown and compared in the next chapter.

4.4 Using measurement data from other instruments

During the CLARA measurement campaigns a lot of information on the atmosphere and clouds was gathered. By introducing this additional data in the Matched Atmosphere Algorithm a more better estimation of the atmosphere can be made, which will lead to a more accurate water vapour and liquid water retrieval. In this section it is described how the data of lidar, radar and radiosondes can be used in the Matched Atmosphere Algorithm.

4.4.1 Lidar cloud base height

During the measurement campaign a lidar fired a laser pulse into the sky (elevation 90°) every 3 seconds. From the reflections of the pulses the cloud base height is obtained.

This cloud base height data can be used as input for the Matched Atmosphere Algorithm. In this case H_{base} is no longer a tuning parameter, instead H_{top} is not put at the 0°C boundary but tuned together with RH_{ref}. As with the original algorithm a look up table is made and V and L are obtained from this. Only now there are three possible situations:

- the lidar detects no cloud,
- the lidar detects a cloud at such a great height that is has to be an 'ice-cloud' (containing no liquid), It is assumed that clouds with a base height higher than the 0°C level are ice-clouds.
- the lidar detects a cloud from which it is presumed it is a 'water-cloud'.

In the first two situation there is no contribution by a cloud to the amount of liquid water and L is mostly equal to 0. The only way that there can be a very small amount of liquid water is when there is an contribution by aerosols which, according to the model (Equation 2.18), are present whenever the relative humidity is between 80% and 99%. The maximum contribution of aerosols is in the order of $3 \cdot 10^{-3}$mm. In case of clear sky conditions or when there is an ice-cloud, the only tuning parameter left is RH_{ref} and therefore the look up table consists points forming a line. Determining V and L for a measured brightness temperature combination is done by finding the nearest point on the line.

In case the base height of the cloud is below the 0°C level, the cloud is assumed to contain liquid water. The cloud base height is used as input for the Matched Atmosphere Algorithm and a look up table is made by varying H_{top} from the cloud base height measured by the lidar to the altitude where the temperature is -5°C . This way a look up table is created that is similar to those in the Matched Atmosphere Algorithm where no lidar information is used. Determining V and L for a measured brightness temperature combination is done by linear interpolation from the nearest 3 points in the look up table. When however the measurement point is outside the convergence area linear extrapolation is used to calculate V and L. In the same way as with the original Matched Atmosphere Algorithm this extrapolation may lead to unreliable results because the measurement points do not agree with the atmosphere model, this might lead to negative water liquid values as will be seen later.

4.4.2 Radiosonde profiles

At times that a radiosonde was launched the temperature, pressure, relative humidity and dewpoint temperature profiles are available. Here the dewpoint temperature is defined as the temperature at which dew is beginning to be formed. The integrated water vapour (V) can be directly calculated from $T(h)$ and $RH(h)$ using equations (2.12), (2.15) and (2.16).

For liquid retrieval the parameters H_{base}, H_{top} and C were left. The cloud base and cloud top were derived from temperature and dewpoint temperature profiles. It was stated that the base of the cloud is at that height where temperature and dewpoint temperature come close together. Whereas the top of the cloud is there where the difference between the temperature and the dewpoint temperature curves increases strongly [9]. When the H_{top} found is above the 0°C level then the latter height is considered to be the top of the cloud. The considerations on which this is based, are that liquid water is assumed to be frozen when temperature is below 0° and frozen water does not change the attenuation in the atmosphere in the range of 20/30 GHz considerably. Thus ice clouds can not be detected with the radiometer.
In formulas this gives for H_{base} :

$H_{base}=h(i)$ if

$$T(i)-DT(i)<3 \ \wedge \ \frac{\partial DT(i)}{\partial h}>0 \ \wedge \ \frac{\partial DT(i+1)}{\partial h}<0$$
$$\wedge \ \left|T(i-1)-DT(i-1)\right| > \left|T(i)-DT(i)\right| \ \wedge \ T(i)>0 \tag{4.3}$$

where: *T is the temperature in °C,*
DT is the dewpoint temperature in °C,
i is the i-th sample of radiosonde data,
h is the height in m.

And for H_{top} :

$H_{top}=h(i)$ if

$$\frac{\partial DT(i+1)}{\partial h}<0 \ \wedge \ \left|\frac{\partial DT(i+1)}{\partial h}\right|<\left|\frac{\partial DT(i)}{\partial h}\right|$$
$$\wedge \ \left|T(i)-DT(i)\right|<7 \ \wedge \ \frac{\partial T(i)}{\partial h}\leq 0 \ \wedge \ T(i)>0 \tag{4.4}$$
$$\vee \ \left(T(i)<0 \ \wedge \ T(i-1)>0 \right)$$

When these criteria are applied to the radiosonde profiles as obtained during the measurement campaigns, this does not result in a useful H_{base} , H_{top} combination in all cases. Reason for this has to be sought in the very dynamic character that the measured atmospheric profiles can have. This is illustrated in Figure 4.4, where temperature, dewpoint temperature and relative hunidity profiles are shown together with the estimations of cloud base and cloud top. From this figure can be seen that the combinations of H_{base} and H_{top} that are found can not be used in the algorithm. Therefore, when cloud base and cloud top have to be estimated from radiosonde profiles, together these criteria one has to look at the profiles in order to verify if the values found are accurate, or if a better estimation can be made.

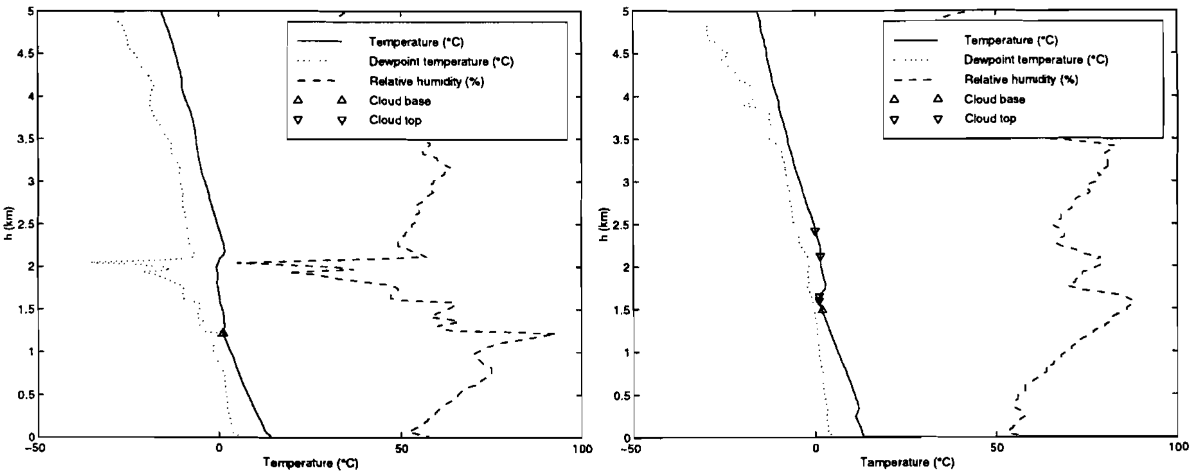


Figure 4.4(a) Cloud base height and cloud top height estimations using criteria (4.3) and (4.4)

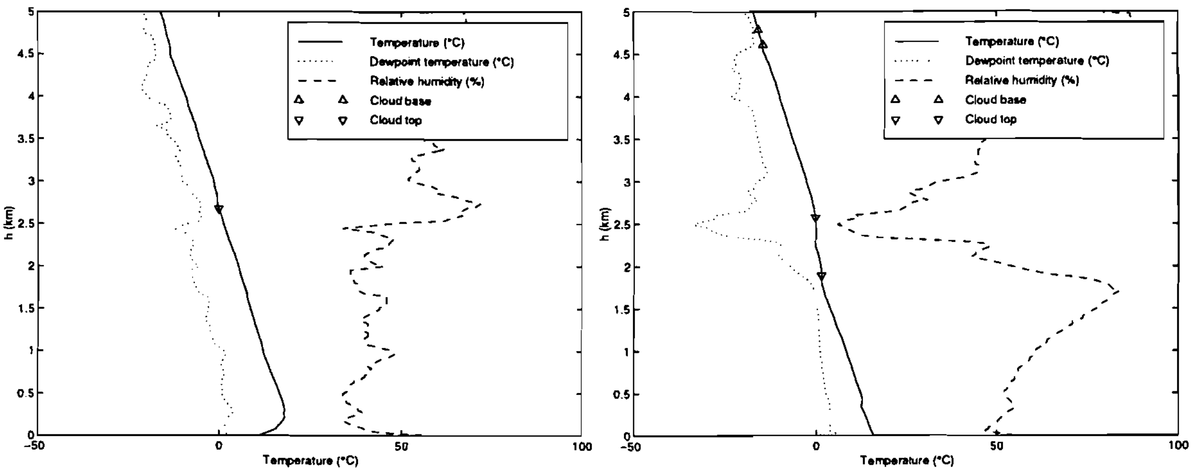


Figure 4.4(b) Cloud base height and cloud top height estimations using criteria (4.3) and (4.4)

Since, during the CLARA measurement campaigns also lidar and lidar data is available the cloud base and cloud top might as well be obtained from these. This probably gives more accurate values for H_{base} and H_{top} .

Having found the base and top of the cloud the liquid water content can be calculated using MPM.

Only the parameter C (2.19) ,which depends on the type of clouds, is left as a tuning parameter. By studying cloud structures Slobin [17] found that C is about half of the adiabatic liquid water content. It is assumed that the value for C lies between 0.1 and 0.75. By calculating the liquid water content L and the corresponding T_{20} , T_{30} combination, for a number of C values within this range, a convergence area is constructed which has the shape of a straight line. Determining the liquid water content L from measured brightness temperatures is done by finding the nearest point on this line.

5. *Comparing the algorithms*

In this chapter the results of the different algorithms for V and L retrieval from radiometer measurements are shown. The objective is to see to what extent the results of the algorithms agree and where they differ.

Another objective is to compare the results of the algorithms with reference values. The problem is that at the moment there is no real reference neither for V nor for L to verify the results. In literature it is found that one takes the amount of water vapour calculated from the radiosonde profiles as mentioned in Section 4.3.2 as a reference value for V. One must however realise that the sensors of the radiosonde have a limited accuracy. This leads to a maximum inaccuracy of $\pm 18\%$ in the retrieval of the amount of water vapour (as will be shown later) and therefore such an comparison is questionable.

At this moment there are no reference data for the verification of the obtained integrated liquid water values either. Maybe in future the amount of liquid water measured by the FSSP can be used as a reference in the comparison of the retrieved L values, but for now these are not available.

For the first and the second CLARA measurement campaign the results of the water vapour and liquid water retrieval by the different algorithms were compared. The first measurement campaign took place from April 15th to April 26th 1996. During this period the sky was clear most of the time, there were only a few very thin clouds as can be seen from the lidar images (which can be found on the CLARA internet site http://www.knmi.nl/PROJECTS/clara). The second CLARA measurement campaign was from August 19th till September 4th 1996. At the time this report was written no lidar or radar images for this period were available but during this campaign there were many more clouds, which can only be seen in the brightness temperatures measured by the RESCOM radiometer.

To show the comparison of the results obtained with the different retrieval algorithms 1 day has been selected from the first CLARA campaign to illustrated clear sky and periods of thin clouds. This day from the first measurement campaign in which there were very few clouds is April 19th 1996. Between 0:00h and 4:00h, there were clouds with a base height of about 2.8km which, as will be shown later are probably ice clouds. Later that day there were a few very thin clouds (about 200m thick) at a height of 1.5km at 4:00am, which were slowly evaporating towards 9:00am. There were radiosondes launched at 6:00h, 12:00h and 18:00h (UTC) that day.

Another day was chosen from the second measurement campaign, to show the results of the different algorithms in case of thicker clouds. During the second measurement campaign there large periods of thick cloud cover and there were also more often periods of rain. The day chosen is September 4th 1996 with a radiosonde launched at 6:00h, 9:00h, 13:00h and 18:00h. Judging from the brightness temperature and liquid water plots there have been some periods of rain between 6:40h and 10:00h that day. This could not be verified because there was no lidar or radar data of the second measurement campaign available yet.

5.1 Thin clouds

As was said, April 19th 1996 was a day with only a few thin clouds. The brightness temperatures measured by the RESCOM radiometer at 21.3 GHz and 31.7 GHz are shown in Figure 5.1.

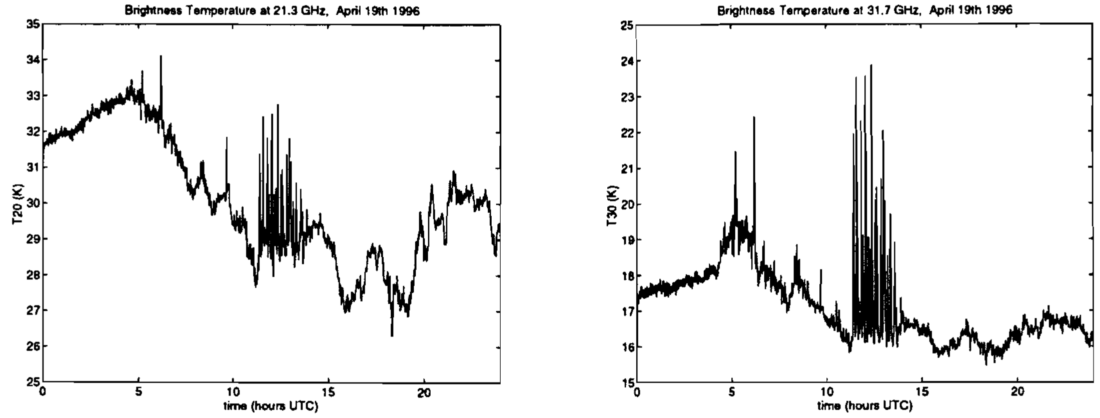


Figure 5.1 (a) Brightness Temperature at 21.3 GHz (b) Brightness Temperature at 31.7 GHz

The period between 11:00h and 14:00h illustrates that the presence of clouds gives a clear increase in brightness temperatures in both channels, where the increase in T_{30} is larger than that in T_{20}. As expected the 30GHz is more sensitive to liquid water.

From these brightness temperatures the integrated water vapour content an liquid water content of the atmosphere are calculated using the different algorithms. The results of the retrievals are shown in the Figures 5.2 and Figure 5.3.

Water vapour

In Figure 5.2 can be seen that the curves corresponding all show the same trends and have more or less the same shape. The most important differences are in the absolute level and in the range.

The result of the CCIR algorithm is shown in Figure 5.2 (a). From this graph can be seen that the values found with CCIR are higher than those of the other algorithms. Also the range of the *V* values is larger.

From Figure 5.2 can be seen that SIGMA-A (c), SIGMA-B (d) and the Matched Atmosphere Algorithm (e) give a curve with almost exactly the same shape, the only difference is the absolute level of the curves.

The Matched Atmosphere Algorithm with as extra input the cloud base height measured from the lidar gives a water vapour curve as shown in Figure 5.2 (f). It can be seen that the values found with this algorithm are about 1 to 1.5 mm lower than those of the regular Matched Atmosphere algorithm. Another difference is the larger variation in *V* from 9:00h until 14:00h. During this time there are large variations in the cloud base height and interruptions in the cloud cover, as can be seen from the lidar picture in Appendix B. Also can be seen that there are more cloud layers above each other during certain periods of time. It can be concluded that by introducing cloud base height information in the Matched Atmosphere Algorithm there is a larger influence of clouds on the amount of water vapour.

Using the so-called 'adaptive linear algorithm' results in the curve as is shown in Figure 5.2 (g). It can be seen that the shape of this curve is very much the same as the curve obtained with the regular Matched Atmosphere Algorithm, only the absolute level is about 0.75mm lower. It can be concluded that approximating the look up tables with flat planes gives very useful results and therefore this simplification seems worthwhile.

Water vapour amounts can be directly obtained from radiosonde data (Figure 5.2 b). When these are taken as a reference, the SIGMA-A algorithm matches these values best; the values at 18:00h corresponds very well, whereas at 6:00h and 12:00h the difference is about 1mm.

The observations made here do not only for this particular day but apply to all days in the first measurement campaign. April 19th has been chosen because it gives a good illustration for the first CLARA campaign.

The reason for the linear algorithms having a different absolute level (and in the case of CCIR a different range) can be found in the fact that the constants used in the algorithms are not tuned for the area of the test site.

The Matched Atmosphere Algorithm gives a result that is constantly about 4 mm higher than the values found with the radiosondes. When the cloud base height obtained from lidar measurements is used as input, this results in a smaller deviation in relation to the vapour values derived from the radiosonde profiles. Still there is a difference of about 2 mm which could be due to:

- a mismatch in the estimated profiles of the standard atmosphere,
- inaccuracy introduced by the modelling assumptions,
  (assumptions as H_{top} being at the 0°C level and RH_{ref} being 100% in a cloud)
- inaccuracy in the brightness temperature measurements,
- inaccuracy in the ground level meteorological data
- inaccuracy of MPM.
- inaccuracy introduced by interpolation and extrapolation

One however has to keep in mind that the water vapour values obtained from the radiosonde profiles are no absolute reference, but there is an inaccuracy of up to 18% in these values. It is therefore not possible to say which of the algorithms gives the most accurate results.

The results of the Matched Atmosphere Algorithm will be look at in more detail in next the chapter.

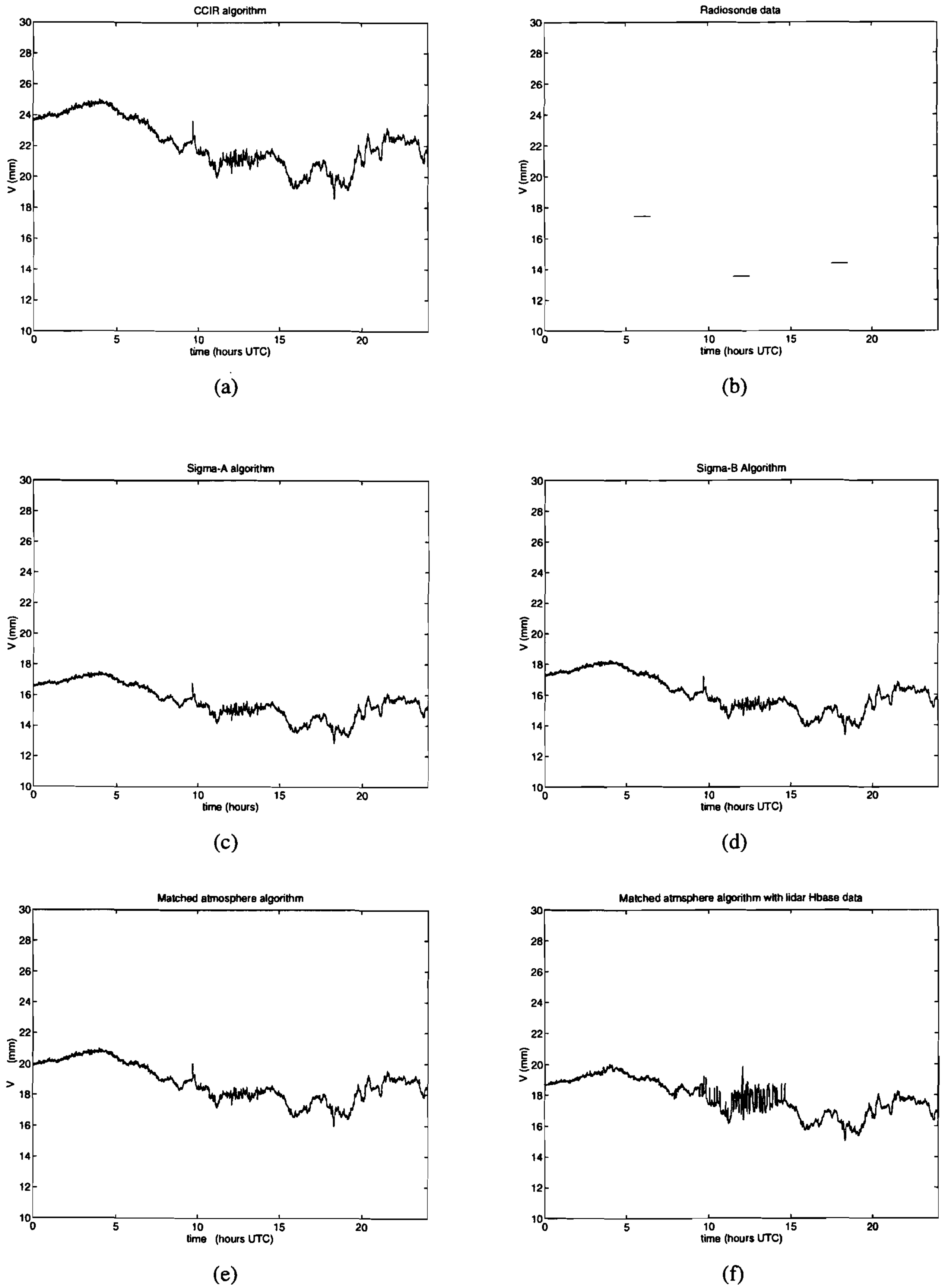
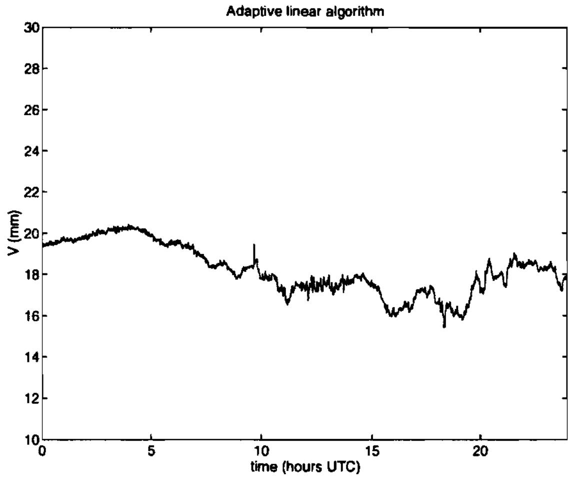


Figure 5.2 Water vapour retrieval, April 19th 1996.



(g)

Figure 5.2 Water vapour retrieval, April 19th 1996.

Liquid water

April 19th was a day with very few water clouds as can be seen from the lidar measurements of that day, shown in appendix B. This is consistent with the very low values that the liquid water plots show, with only a contribution in the periods that there are thin clouds (from 4:00h until 10:00h and from 12:00h until 14:30h). The cloud that can be seen in the lidar picture in the period from 0:00h until about 4:00h, has a base height of approximately 2.8km. The temperature at ground level during this period is around 11°C. According to the adiabatic lapse rate of -6.5°/km, the temperature at the cloud base would be -7.2°C, which implies that all water it contains is frozen. The fact that this cloud is not detected by the 20/30GHz radiometer is consistent with the assumption that ice clouds are not detected by this instrument.

From the integrated liquid water plots can be seen that all algorithms give negative values during certain periods of time. This is of course physically impossible and therefore these values are definitely too low; they should have been on zero-level. There is clearly an inaccuracy in the obtained results for periods of clear sky or periods in which there are very thin clouds.

When the liquid water graphs are compared to the plot of the lidar cloud measurement (Appendix B) it can be seen that all algorithms detect the clouds. They give higher L values during periods when there are water clouds present and no increase in case of ice clouds.

In Figure 5.3 can be seen that the CCIR algorithm gives the lowest integrated liquid water values with the smallest range. Same as with the water vapour retrieval this is due to a the constant used in the algorithm which are not tuned for the specific test-site. Deriving parameters for the test-site in Delft could result in more accurate results. Another possible reason for the negative water liquid values that are obtained, is that the assumption of the linear relation between brightness temperatures and the amount of liquid water (3.3), (3.11) and (3.13) does not hold in clear sky conditions.

In contrast to the CCIR and Matched Atmosphere Algorithm, SIGMA-A and SIGMA-B give considerable variations in L during periods when there are no clouds. Further investigation learned that these variations were not caused by the introduction of ground level meteorological data in case of SIGMA-A, or annual periodicity of these variables in case of SIGMA-B. When these influences were left out of these algorithms the same variations remained present.

The results of the Matched Atmosphere Algorithm in which the cloud base height obtained from lidar measurements is used, are depicted in Figure 5.3(f). From this picture can be seen that whenever there is no cloud detected from the lidar, the calculated amount of liquid water is equal to zero. When no cloud is detected, H_{base} is equal to H_{top} and from Equation (2.19) results that there is no contribution from clouds to the liquid water density profile. The only way in which there can be a little amount of water (when rain is not taken into account) is when there is an contribution by aerosols. During periods in which there are clouds detected by the lidar, the method of calculating the amount of liquid water is comparable to that used in the regular Matched Atmosphere algorithm. In this case a look up table is created by varying the parameters RH_{ref} and H_{top} as described in Section 4.4.1. Due to extrapolation also here negative values of L are found during clear sky periods or with very thin clouds.

Elimination of the influences of pressure and temperature from the SIGMA-A and SIGMA-B algorithms leads to a linear retrieval of L in both cases. By calculating the parameters for this linear retrieval we find :

SIGMA-A: $L=-0.29\cdot\tau(20)+4.52\cdot\tau(30)+1.30$

SIGMA-B: $L=-0.22\cdot\tau(20)+4.489\cdot\tau(30)-0.22$

CCIR: $L=-3.04\cdot\tau(20)+6.89\cdot\tau(30)-0.152$

It can be seen that in the SIGMA-A and SIGMA-B algorithms, compared to the CCIR algorithm, the attribution of $\tau(30)$ is relatively much larger than that of $\tau(20)$. Thus the SIGMA algorithms are much more sensitive to changes in T_{30} and therefore show more variation where for the other algorithms the L values are rather stable. It can be concluded that the SIGMA algorithms, as they are implemented now are not useful for the retrieval of liquid water contents. When a linear algorithm is used one would rather chose the CCIR algorithm, preferably with parameters tuned for the specific test-site.

Judging from the curve obtained with the Matched Atmosphere Algorithm it is expected that there is a negative offset in the results. When the curve is moved up about 0.045 mm the lowest obtained values area at the zero-level and therefore agree better with reality. Also in this case inaccuracies in the results of the Matched Atmosphere algorithm could be due to: a mismatch in the estimated profiles an the real atmosphere (clear sky situations are not modelled accurately by standard profiles), inaccuracy in the brightness temperature measurements or inaccuracy of MPM.

When the adaptive linear algorithm is used to calculate the integrated liquid water contents, Figure 5.3 (g), it can be seen that the results agree well with those of the regular Matched Atmosphere Algorithm, when the L values exceed the level of -0.025mm. For lower values there is some deviation which leads to undesired variations in the level in case of the adaptive linear algorithm. It can be concluded that this approximation is useful for retrieving L but introduces inaccuracy for low liquid values. Thus this linear approximation is not valid in clear sky conditions.

Same as with the water vapour retrieval, it has to be remarked that the observations made on basis of the calculations of liquid water contents for September 4th are illustrative for the other days in this measurement campaign.

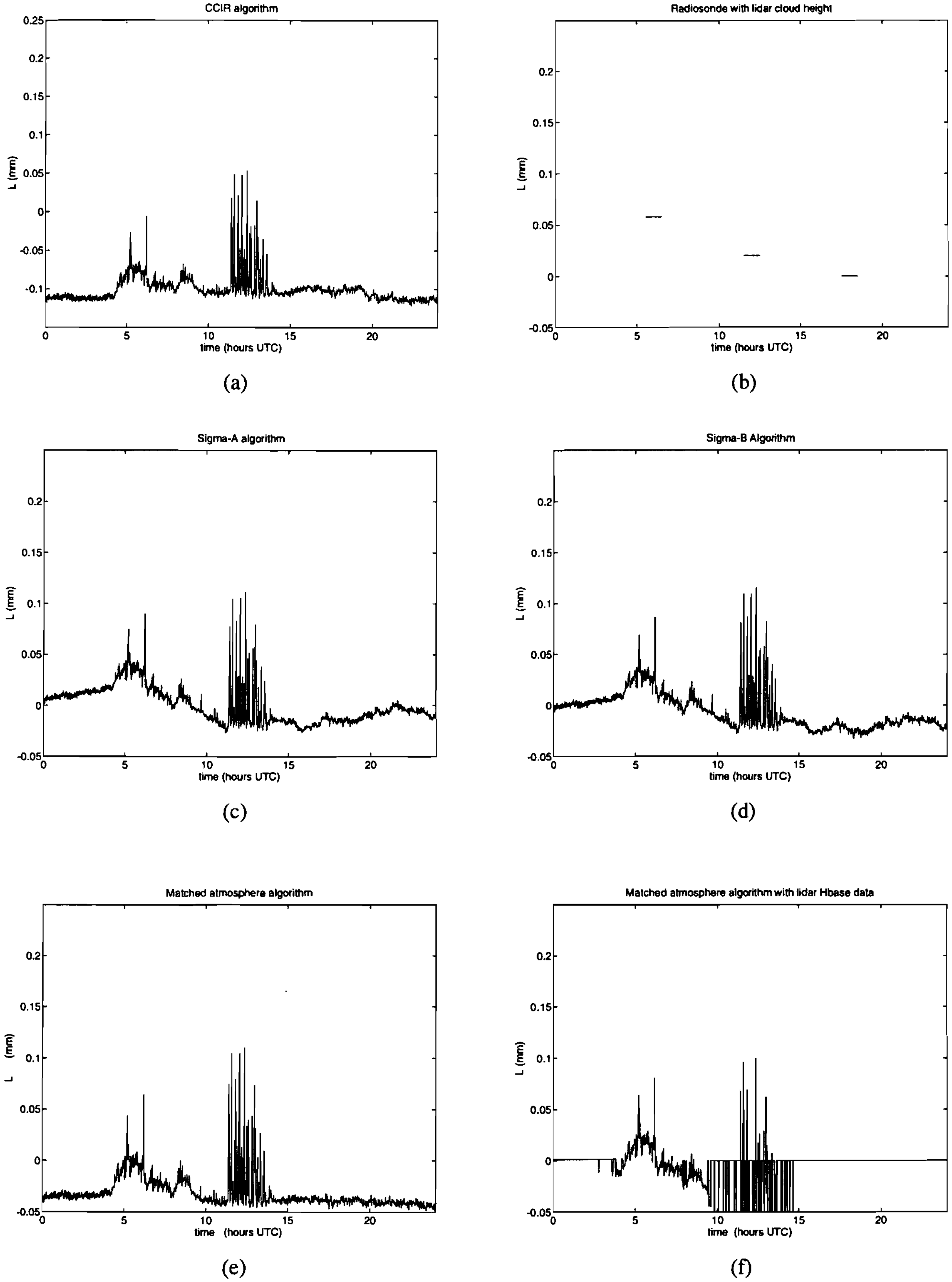
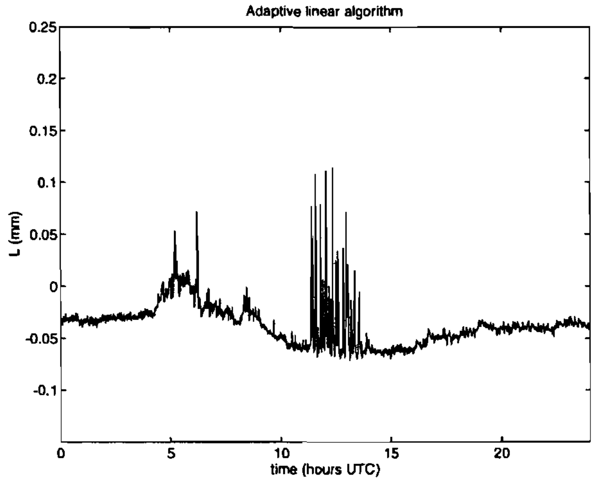


Figure 5.3 Liquid water retrieval, April 19th 1996.



(g)

Figure 5.3 Liquid water retrieval, April 19th 1996.

5.2 Thick clouds

The brightness temperatures measured by the radiometer on September 4th 1996 are shown in Figure 5.4.

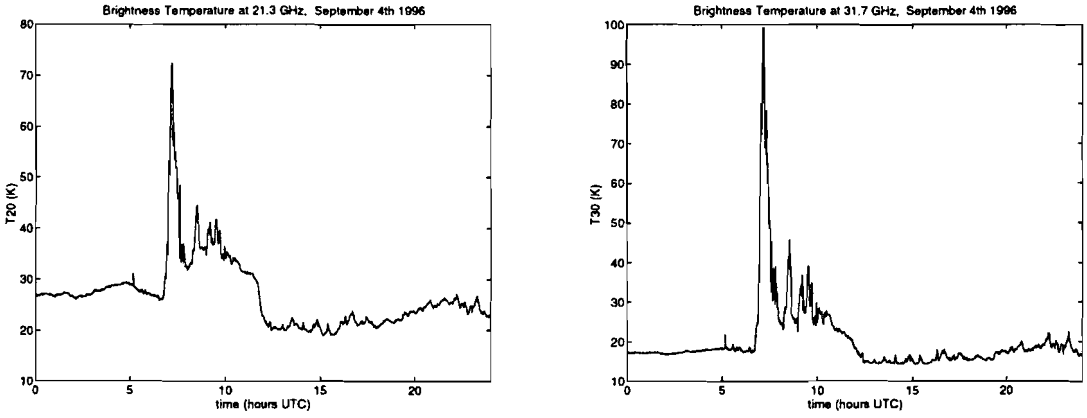


Figure 5.4 (a) Brightness Temperature at 21.3 GHz (b) Brightness Temperature at 31.7 GHz

From these brightness temperatures *V* and *L* are calculated using the different algorithms. The result of the water vapour and liquid water retrieval for this day are shown in Figure 5.5 and 5.6 respectively.

Water vapour

In all graphs a strange sort of abrupt change can be seen between 7:00h and 7:40h. When for this period the liquid plots are examined one can notice that during this period the liquid values are very high which indicates that it is raining. Within the framework of the CLARA campaign we are only interested in clouds, therefore periods of rain (when *L>0.25mm*) are not taken into account.

The CCIR linear algorithm, figure 5.5 (a), gives a curve that has a higher absolute level then those of the others methods and also has a larger range.

The SIGMA-A, SIGMA-B and Matched Atmosphere Algorithm give curves with exactly the same shape. The only difference is the level. The deviation of the linear algorithms is, like in the case of thin clouds, due to mistuning of the constants that are used or non-linearity in clear sky conditions.

At the time this report was written there was no lidar cloud base height data available, therefore this information could not be used in the Matched Atmosphere Algorithm as was done for April 19th.

When the vapour values calculated from the radiosonde are taken as a reference, the Matched Atmosphere Algorithm give a curve that matches these best.

The results of the adaptive linear algorithm are shown in Figure 5.5 (f). The curve has exactly the same shape as that obtained with the regular Matched Atmosphere Algorithm, only the absolute level is lower but only less than 1mm. This confirms the conclusion that the linear approximation of the look up table leads to a very useful way to retrieve the amount of water vapour.

Liquid water

In Figure 5.6 the liquid water curves obtained with the different algorithms are shown. It can be seen that also here all methods give negative values in certain periods of low atmospheric humidity. As has been said this should not be possible.

In the periods where the integrated water liquid exceed the level of 0.25 mm it was probably raining, so we are not interested in these.

At the time this report was written there was no lidar or radar data on cloud heights available. Instead the criteria as described in Section 3.3 were used to find the cloud base and the cloud top from the radiosonde profiles. In cases the cases that these criteria did not lead to a useful combination, the profiles were inspected visually to see if there was a cloud. If so the base and top were estimated from the profiles. Using the radiosonde profiles together with the estimated cloud heights this resulted in the water liquid values as shown in Figure 5.6 (b).

The CCIR algorithm gives values for L that are further beneath the zero-level than those of the other algorithms. A better tuning of the parameters used in this algorithm is therefore desirable.

The SIGMA-A and SIGMA-B algorithms give a result that is almost the same as that of the Matched Atmosphere Algorithm. Only in the period from about 12:00h until 19:00h SIGMA-A and SIGMA-B give values that are about 0.04 mm lower then those of the Matched Atmosphere Algorithm and thus further below zero. This again illustrates the fact that the SIGMA algorithms have undesired variations in the liquid water level where other algorithms give steady results. This again can be appointed to a to larger sensitivity to brightness temperature changes in the 30GHz channel.

Mistuning of the constants together with non-linearity in clear sky conditions is again probably the reason for the wrong absolute level of the integrated water liquid values calculated with the linear algorithms.

The Matched Atmosphere Algorithm gives values that are just below zero. From this it can be concluded that the absolute level is slightly too low. Possible reasons for this were already mentioned in the previous section.

Furthermore it can be seen that the curve obtained with the adaptive linear algorithm, Figure 5.6 (f), in general agrees quite well with the results obtained with the regular Matched Atmosphere Algorithm although on some points deviations can be observed. This simplification of the Matched Atmosphere Algorithm can surely be used to get a real-time impression of the liquid water contents.

Finally it has to be noted that the observations made, based on this particular day, also apply for the other days of the second CLARA measurement campaign. September 4th was chosen as an illustration of the rest of the measurement results.

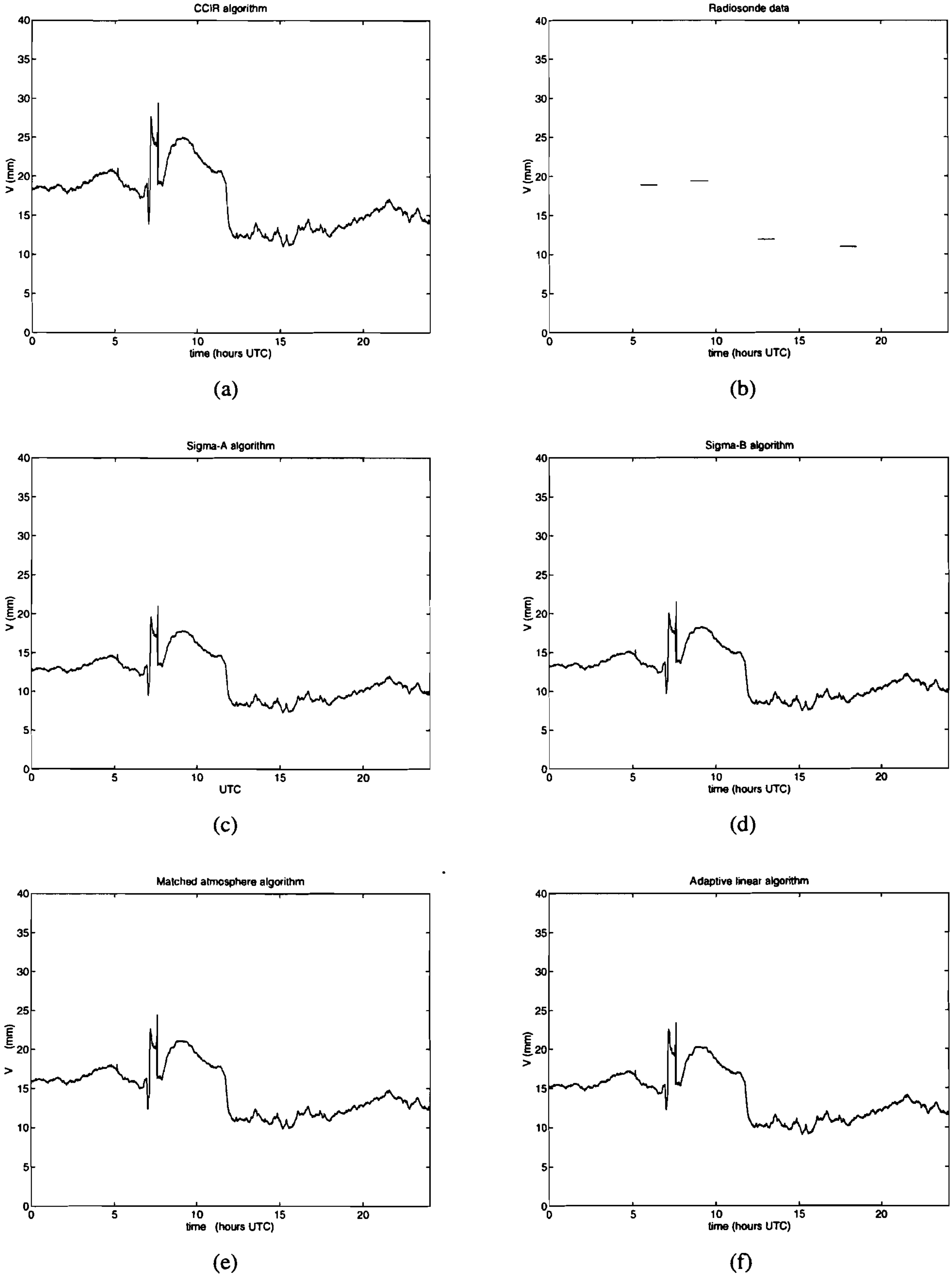


Figure 5.5 Water vapour retrieval, September 4th 1996.

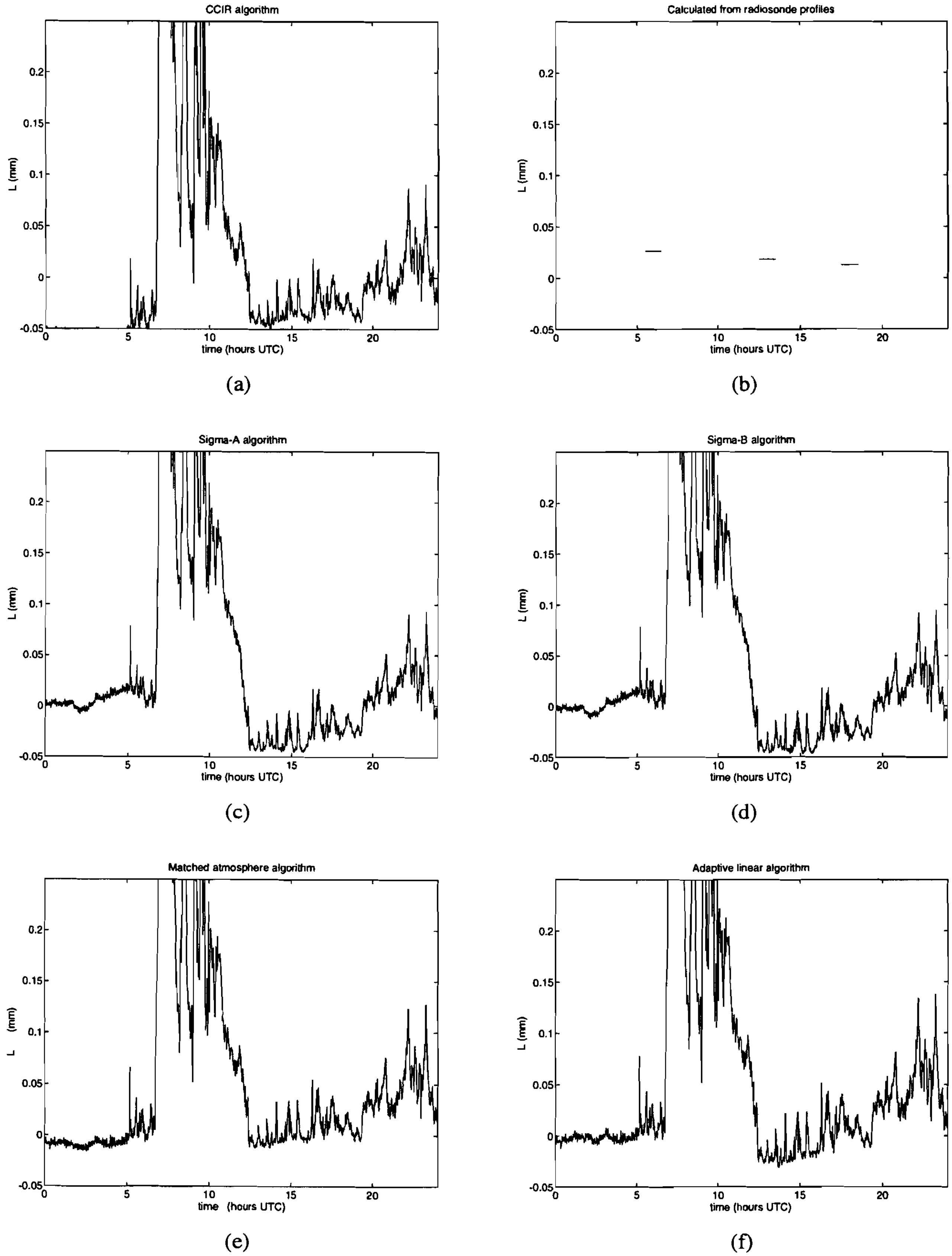


Figure 5.6 Liquid water retrieval, September 4th 1996.

5.3 Conclusions

Several different water vapour and liquid water retrieval algorithm have been examined. All of these algorithms give *V* and *L* curves that have about the same shape. When the water liquid plots are compared with pictures of the lidar cloud measurements, it can be seen that all algorithm manage to detect clouds well. During clouded periods a clear increase in *L* can be seen in the curves obtained with all retrieval algorithms. In the water vapour curves the presence of clouds has very little effect. It is therefore possible to determine integrated amount of water vapour and cloud liquid from microwave radiometric data.

All algorithms give negative liquid values during periods of clear sky or when the clouds are very thin. These negative liquid water values are of course physically impossible.

The main difference between the curves is in the absolute level and range. It is not possible to determine which algorithm gives the most accurate results because there are no real reference values.

The linear algorithms are based on long term statistical observations. An improvement of these algorithms could be made by tuning the parameters that are used to the specific test site. For this a large number of combined radiosonde/radiometer measurements should be available.

A possible reason for the negative water liquid values that are obtained with the linear algorithms, is that the assumption of the linear relation between brightness temperatures and the amount of liquid water does not hold in clear sky conditions.

In the liquid water curves obtained with the SIGMA-A and SIGMA-B algorithms variations can be seen during periods when there are no clouds. The other algorithms are at a steady level during these times. It was shown that the variations in liquid level are caused by a too large sensitivity to changes in the brightness temperature in the 30GHz range. For this reason it is not recommendable to use the SIGMA algorithms, for the retrieval of liquid water.

For now there is more interest in the Matched Atmosphere Algorithm because it is developed to use actual meteorological data (ground level meteorological measurements and optional cloud height or atmospheric profiles) and is therefore more flexible. From the results obtained so far it can be concluded that, during periods clear sky or with very thin clouds, the Matched Atmosphere Algorithm gives liquid water values that are too low and water vapour values that are probably slightly too high. Reasons for the negative liquid values have to be sought in

- a mismatch in the estimated profiles of the standard atmosphere,
- inaccuracy introduced by the modelling assumptions,
  (assumptions as H_{top} being at the 0°C level and RH_{ref} being 100% in a cloud)
- inaccuracy in the brightness temperature measurements,
- inaccuracy in the ground level meteorological data,
- inaccuracy introduced by interpolation/extrapolation
- inaccuracy of MPM.

In the next chapter the sensitivity of the Matched Atmosphere Algorithm to variations in input variables, tuning parameters and profiles will be examined in more detail.

6. The Matched Atmosphere Algorithm

The Matched Atmosphere Algorithm is the method of water vapour and liquid water retrieval that we are most interested in at the moment because it is most flexible, as it not only uses ground level meteorological data, but also estimations of the real atmosphere in calculations. For this reason it is expected that, when a good estimation of the atmosphere is made, it is possible to obtain more accurate results than the linear algorithms.

In this chapter the accuracy of the Matched Atmosphere Algorithm is looked at in more detail. As there is no absolute reference to validate the obtained results, it is not possible to make a statement about the exact accuracy of the algorithm. It is however possible to examine the sensitivity of the algorithm to input parameters and profiles.

Therefore, first it has been examined how good the temperature, humidity and pressure profiles are matched and how sensitive the calculation of brightness temperatures is to variations in temperature, pressure and relative humidity profiles.

Next the influence of parameters used in the modelling of the atmosphere like ground values of *P*, *T* and *RH*, cloud height, cloud thickness are investigated.

Finally the result obtained with the Matched Atmosphere Algorithm are compared with those of other measurement instruments and some conclusions are drawn.

6.1 Atmospheric Profiles

An essential step in the algorithm is that the of *T*, *P* and *RH* are estimated using the actual ground values as was described in Section 3.2. For the pressure a near to perfect match between the estimated profile and the profile measured by the radiosonde has been found. The reason for this is that a radiosonde calculates its actual height from the pressure it measures using (3.15).

To compare the modelled temperature and relative humidity profiles with those measured by radiosondes both curves have been plotted in one graph. From the relative humidity profiles it is hard to see the effect on the integrated water vapour and liquid water amounts, therefore the total humidity profiles are plotted too. The total humidity is the sum of the water vapour density and the liquid water density, in formula this is:

$$Total\ Humidity = v + w \qquad [g/m^3] \tag{6.1}$$

where: *v is the water vapour density as stated in Equation 2.11*
w is the liquid water density as stated in Equation 2.14

For all radiosonde launched on April 19th and September 4th the above mentioned profiles are shown in Appendix C.

From these graphs a number of things can be seen:

- The matched CCIR standard temperature profile does not in all cases correspond well with the temperature profile measured by the radiosondes. From the graphs of April 19th it can be seen that the temperature profiles at 18:00h agree well, whereas at 6:00h the matched temperature is up to 7 degrees too low and at 12:00h up to about 5 degrees too high. Recalling Equations 2.14 and 2.17, it can be concluded that these discrepancies in temperature profiles result in errors in v and w and therefore in the water vapour and liquid water amounts. The influence of mistuning in temperature profiles will be discussed later.

- The relative humidity profiles have a very dynamic character and are therefore hard to approximate with a piece-wise linear profile as proposed by Peter and Kämpfer. Furthermore it can be observed that when the matched temperature profile and the radiosonde temperature profile do not agree well, this is also the case for the relative humidity profiles. Discrepancies between the matched CCIR relative humidity profile and the real profile influence both V and L. While examining the profiles one should be aware of the fact that the radiosonde measures relative humidity with an inaccuracy of 10% till 15% depending on the humidity level and the presence of abrupt changes in humidity.

- The Matched Atmosphere Algorithm assumes the top of a cloud being at the height where the temperature is 0° C. Looking at the graphs in Appendix C it can be seen that this assumption in many cases does not hold. The specific situations of April 19th at 12:00h and September 4th at 12:00h are good illustrations of the Matched Atmosphere Algorithm finding a wrong cloud height. In the first case the real height of the cloud top is approximately 1.8km while the Matched Atmosphere Algorithm finds a height of 2.6km. In the latter case this is 1.1km and 2.5km respectively, a difference of 1.4km. As can be seen in the graphs of Appendix C, clouds are almost always just underneath a temperature inversion. When temperature inversions can be determined by means of radiosonde or radio acoustic sounding system (RASS), the corresponding cloud top height could be better used than the 0° C level. The deviation between the real cloud height and the height found with the Matched Atmosphere Algorithm will influence both V and L, how exactly will be shown later.

- The total humidity profiles plotted in Appendix C give a better idea about how the deviations of temperature and relative humidity profiles from the radiosonde profiles influence the amounts of water vapour and liquid water. From these graphs can be seen that the influence of deviations in temperature and relative humidity profiles at great height is much less than deviations at smaller altitudes. It is therefore important to make an estimation of temperature and relative humidity for the first 5 km above ground level as accurate as possible.

6.1.1 Weighting functions

Now it has been noticed that making a good estimation of the atmosphere for the first kilometers above ground level is important, it has been examined which of the profiles has the largest influence on the final results of the algorithm. In [10] Westwater, Snider and Falls determined the sensitivity of the brightness temperature calculated with MPM to the different profiles. As was shown in Chapter 2, brightness temperature and absorption are related to the atmospheric profiles of T, P, v and w. This relation is non-linear. However to gain insight in how small changes in meteorological profiles give rise to small changes in brightness temperature linearisation is useful.

The sensitivity to a small deviation from an initial profile as a function of height is verified using so-called weighting functions:

$$\delta T_b = \int_0^\infty W_T(h)\delta T(h)dh + \int_0^\infty W_P(h)\delta P(h)dh + \int_0^\infty W_v(h)\delta v(h)dh + \int_0^\infty W_w(h)\delta w(h)dh \qquad (5.1)$$

where: W_T *is the weighting function for temperature [km⁻¹]*
W_P is the weighting function for pressure [K/km/mbar]
W_v is the weighting function for water vapour density [K/km/g/m³]
W_w is the weighting function for liquid water density [K/km/g/m³]
$\delta T(h)$ is the change in temperature profile at height h
(analogous for the other variables)

To be able to interpret the meaning of weighting functions, some explanation may be useful. Take for instance the temperature weighting function W_T. If there is a change of δT [K] in temperature over a height interval δh [km], the brightness temperature response δT_b [K] to this change is $\overline{W_T}\delta T\delta h$, where $\overline{W_T}$ is the average of W_T over the interval δh. Similar considerations lead to the weighting functions for the other variables.

The weighting that Westwater (et al.) finds are shown in [10] Figure 1. To check if we find the same sensitivities, the weighting functions were calculated too. This leads to the results as shown in Figure 6.1.

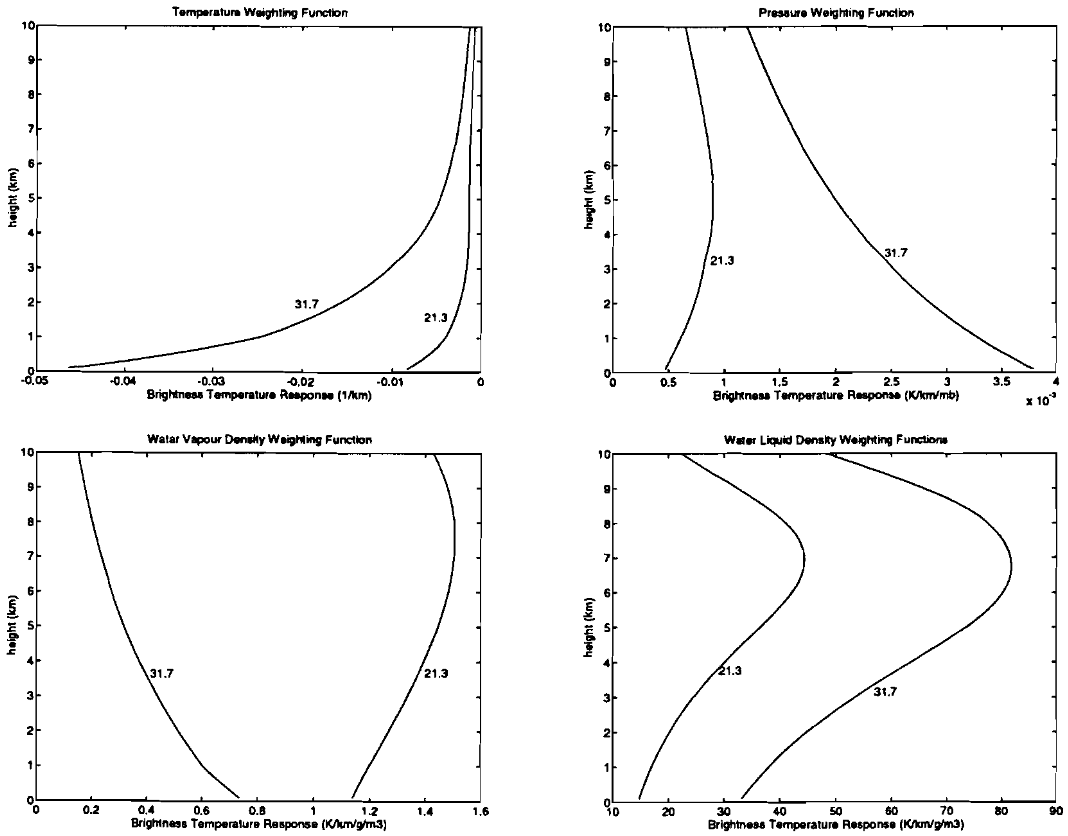


Figure 6.1 Weighting functions

When the weighting functions shown in Figure 6.1 are compared to those in [10], it can be seen that the curves have the same shape and the same order of magnitude. The fact that they are not exactly identical can be explained by the fact that the weighting curves strongly depend on the initial profiles that are used. In [10] these are the 'Denver mean winter profiles' (which are not further specified) whereas we use the CCIR standard atmosphere (with ground values *T(0)=15°C, P(0)=101.3 kPa, RH(0)=60%, R(0)=0 mm/hour* and no cloud).

It can be seen that the pressure and temperature profiles, used as input for MPM, have very little effect on the calculated brightness temperatures, whereas water vapour density (v) and especially cloud liquid density (w) have a considerable influence. In the Section 2.2 it has been shown how v and w depend on the temperature and relative humidity profiles. This brings us to the more interesting question of how the total brightness temperature dependence on the temperature profile and the relative humidity profile is. Or in other words how deviations between the matched profiles and the real atmosphere affect the resulting brightness temperatures. To examine this, weighting functions for the total algorithm were made, these are shown in Figure 6.2.

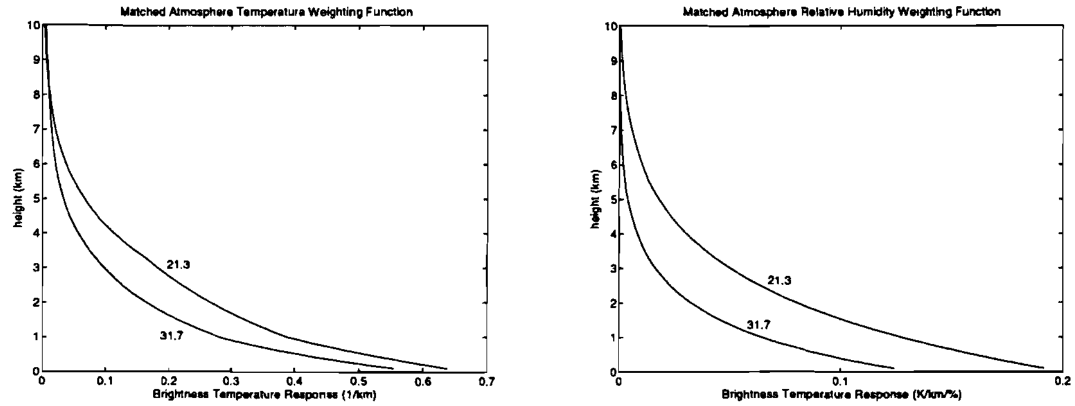


Figure 6.2 Temperature and Relative Humidity weighting functions for the total algorithm.

From these weighting functions can be seen that the brightness temperatures calculated by MPM are more sensitive to changes of 1K in temperature than to changes of 1% in relative humidity. From this can be concluded that it is of most importance to have a good estimation of the temperature profile or if possible to use profiles measured from radiosonde or radio acoustic sounding. Another option, which is currently worked on, is to apply an additional radiometer in 50GHz range to obtain a number of temperature reference points at different heights.

Finally it has to be remarked that the weighting functions can not be used to calculate absolute brightness temperature error values, introduced by deviations from the real atmospheric profiles. Reasons for this are that the weighting functions depend strongly upon the initial profile and the linearisation does not hold for larger deviations.

6.1.2 Cloud height and thickness

As was seen from the comparison of the temperature and relative humidity profiles is, that the cloud height and cloud thickness found with the Matched Atmosphere Algorithm differ considerably from the values that are obtained from radiosonde measurements or lidar data. To get an impression of what effect these deviations have on the brightness temperatures, water vapour content and liquid water this was examined for a particular case.

First this was done for the cloud height. The calculations were carried out on basis of a CCIR standard atmosphere; ground values $T(0)=15°C$, $P(0)=101.3kPa$, $RH(0)=60\%$, $R(0)=0$ *mm/hour* and $RH_{ref}=50\%$. In this atmosphere the base height of a 500m thick cloud is varied from 1km to 2.5km. The effect this has on the brightness temperature at 21.3GHz, the brightness temperature at 31.7GHz, water vapour content and liquid water content is illustrated in Figure 6.3. From these graphs can be seen that the dependence in all cases is nearly linear. In percentage the effect of a deviation in cloud base height on L is larger than the effect on V. When for instance, for reasons of mistuning, the cloud base is placed at 1.5km instead of at 2km this results in a 14% increase in V and a 21% increase in L which is considerable. Again these values are for one particular case (one specific atmosphere) and no general statements can be made on the error introduced due to deviations in cloud base height. The conclusion to be drawn from the preceding observations is that information about cloud height in the Matched Atmosphere Algorithm will give a slight improvement in the inaccuracy of the results.

To illustrate the deviation between the cloud base height that the Matched Atmosphere Algorithms finds and the cloud base height that is obtained from lidar measurements, results are shown in Figure 6.4 for April 19th 1996. (The cloud base height found by the Matched Atmosphere Algorithm is only plotted if $H_{base}<H_{top}$, in other cases, according to the algorithm there is no cloud). First thing that can be noticed is that the lidar measures ice clouds whereas the radiometer is not able to detect these. Furthermore it can be seen that the cloud base height used in the Matched Atmosphere Algorithm is 500m to 1km higher that the real cloud base height. A reason for this is that the Matched Atmosphere Algorithm uses the 0°C level as the top of the cloud then searches for a cloud base height which leads to the best match in brightness temperatures. As was seen earlier, assuming the cloud top being at the 0°C level does often not agree with reality. In this particular case is the cloud top at a level where the temperature is above 0°C (See Appendix C) and therefore the Matched Atmosphere Algorithm estimates a cloud top that is too high.

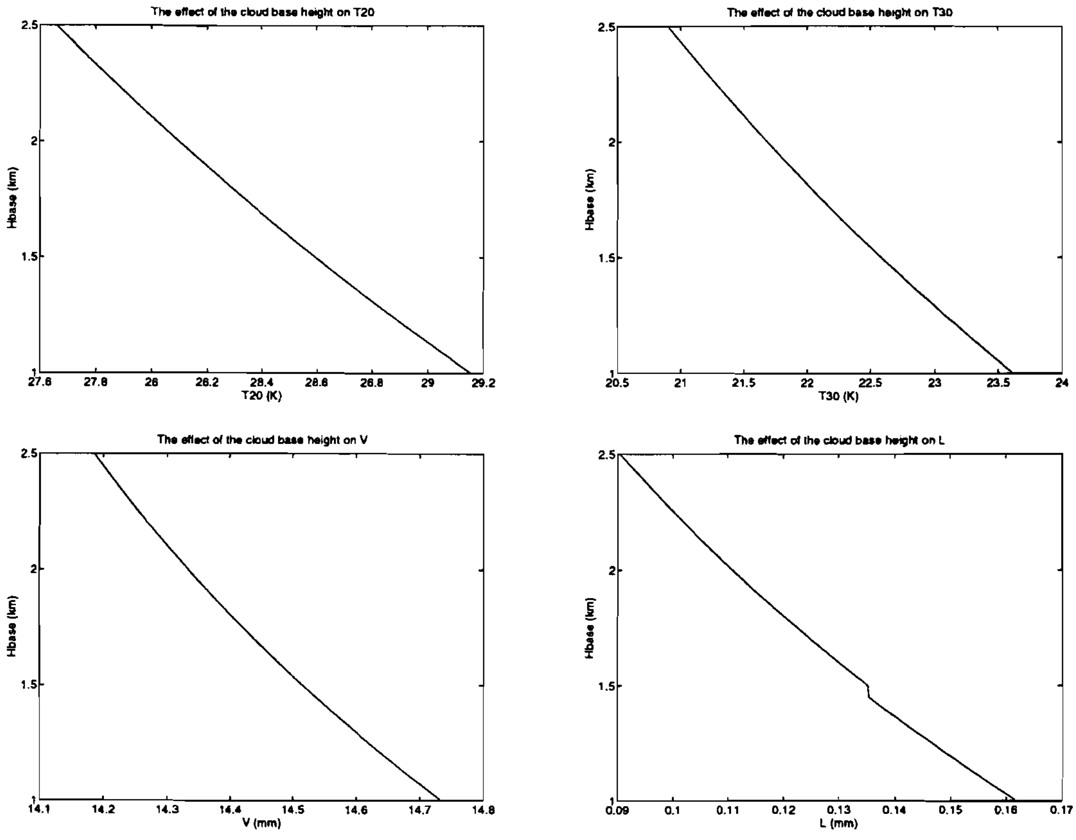


Figure6.3 The effect of the cloud height on T20, T30, V and L

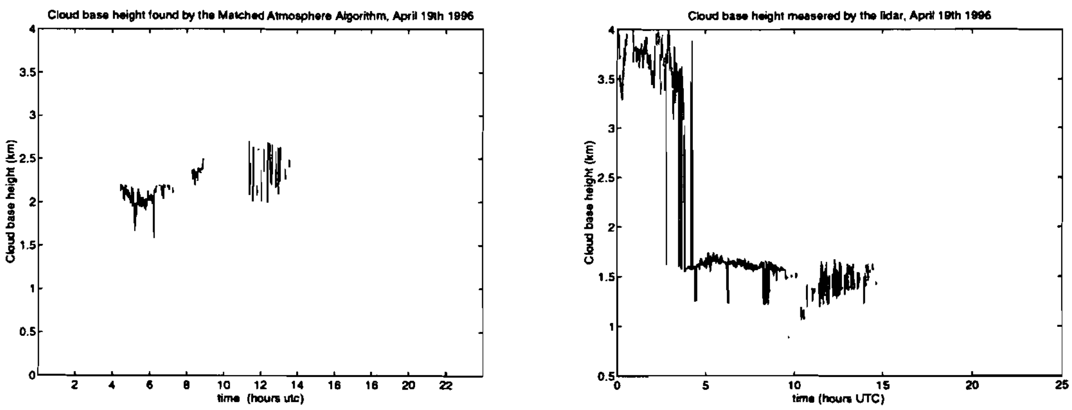


Figure 6.4 Cloud base height found by the Matched Atmosphere Algorithm and cloud base height measured by the lidar

In the same way as was done for the cloud height also the influence of the cloud thickness has been examined. Now the cloud top was kept on a fixed height of 1.9km and the cloud base was varied from 1.9km (no cloud) down to 0.9km resulting in a cloud with a thickness of 1km. The rest of the conditions were the same as in the previous calculations. The effect the cloud thickness has on *T20, T30, V* and *L* is shown in Figure 6.5.

From this graphs can be seen that the relation between the cloud thickness and *T20, T30* and *L* is quadratic, whereas for *V* this is nearly linear. Also can be noticed that a deviation in cloud thickness has a considerable effect on *V* but especially on *L*. From this observation can be concluded that a good estimation of the cloud thickness is essential to get accurate results for water vapour and liquid water content. As can be seen from the profiles in Appendix C, the cloud thickness is in most cases estimated quite well by the Matched Atmosphere Algorithm.

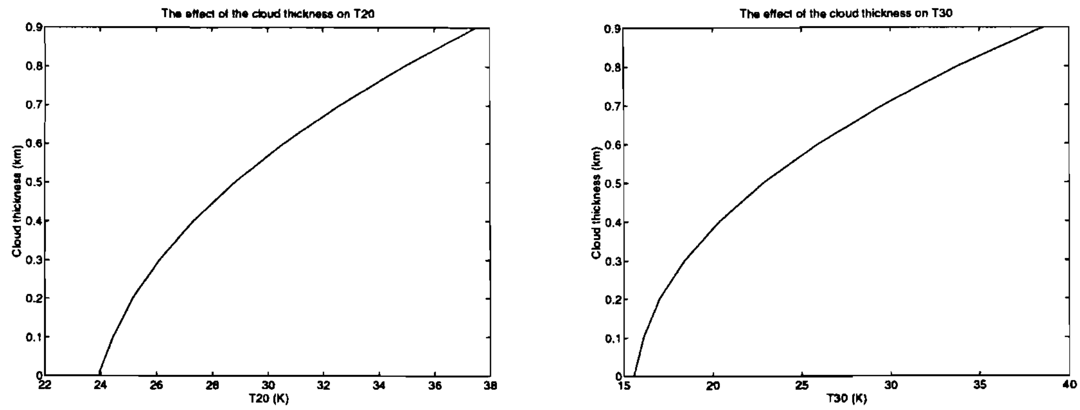


Figure 6.5(a) The effect of could thickness on T20, T30.

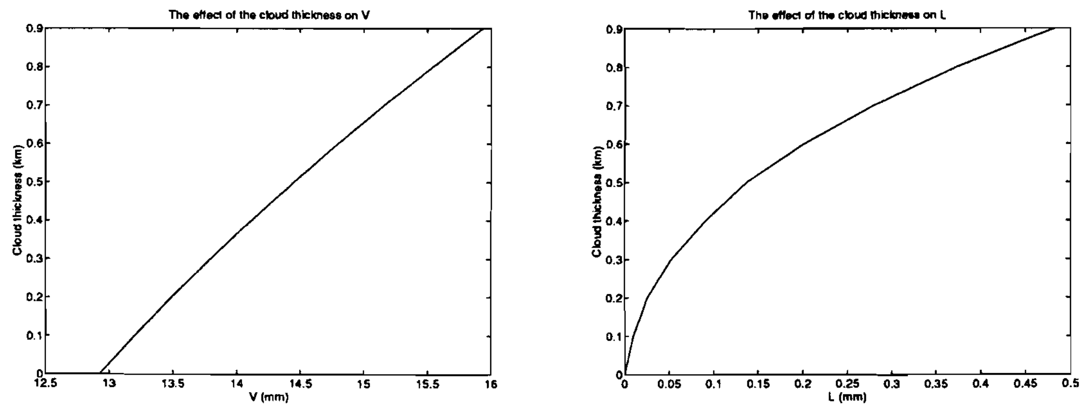


Figure 6.5(b) The effect of could thickness on V and L.

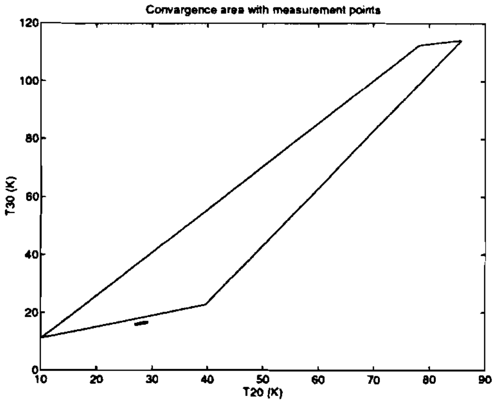
6.2 Ground level meteorological data

In the Matched Atmosphere Algorithm an estimation of the actual atmosphere is made, based on the measured ground level values of temperature, relative humidity and pressure, as is described in Section 3.2. When the ground level values, *T(0)* ,*RH(0)* and *P(0)*, are determined, the estimated temperature profile and pressure profile are fixed. From the temperature profile the cloud top is determined (the 0°C level) and therefore this is directly related to the ground temperature too. In the relative humidity profile are two parameters to be tuned, namely H_{base} and RH_{ref}. By varying these parameters over their full range, (H_{base} from 0.1km to H_{top} and RH_{ref} from 0 to 100%) after calculating the corresponding brightness temperatures, *V* and *L*, a lookup table is made. The set of all possible brightness temperature combinations that is obtained this way, is called the convergence area. Now when the brightness temperatures T_{20} and T_{30} measured by the radiometer are available, the Matched Atmosphere Algorithm calculates the corresponding *V* and *L* values from lookup table, using linear interpolation.

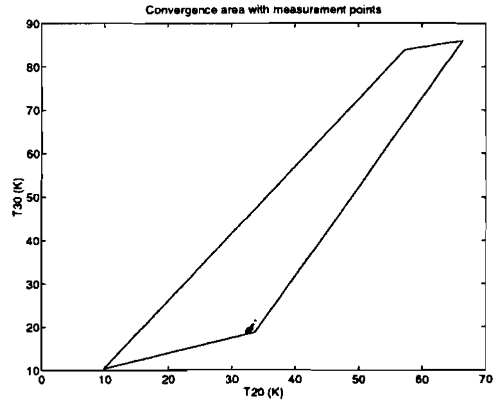
Having carried out these calculations on the radiometer measurement data of the first and the second CLARA campaign, three typical situations can be distinguished:

- Periods of clear sky: for instance April 19th, between 15:00h and 16:00h.
- Thin clouds: for instance April 19th, between 5:00h and 6:00h.
- Thicker clouds: for instance September 4th, between 10:00h and 11:00h.

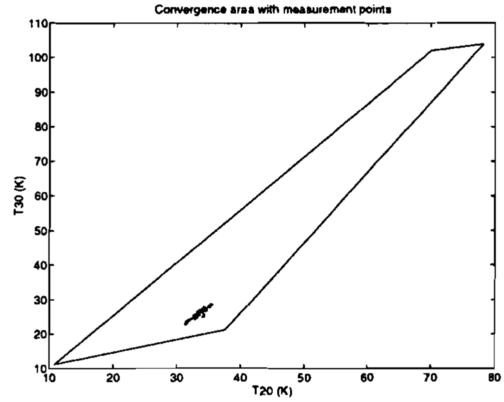
For all those three situations the convergence area together with the measured brightness temperatures are shown in Figure 6.6.



Clear sky



Thin clouds



Thicker clouds

Figure 6.6 Convergence area with measurement points

From this figure can be seen that for thin clouds the measured brightness temperatures are on the edge of the convergence area. In clear sky conditions the measured values are just outside the convergence area, the V and L values for these points are calculated from the lookup table using extrapolation. Measurement points outside the convergence area are contradictory to the model and result in unreliable water vapour and liquid water values. This can clearly be seen from the negative liquid water amounts that are found in clear sky conditions and in periods with very thin clouds. It can be concluded that for these conditions either the modelling of the atmosphere is not accurate or the radiometer data are incorrect.

To see what the influence of the ground level meteorological data on the atmosphere model is, a closer look has been taken to how the convergence area and the lookup table change under various ground level conditions. One objective of this examination is to see if inaccuracy in measurement of T_s, RH_s or P_s can be a reason for the model not complying in case of the atmosphere having a low humidity. By virtue of this, the measurement points outside the convergence area could be explained and with this the negative liquid water amounts that are found also.

Another point which could be observed is the influence of the ground level meteorological data on the results of the Matched Atmosphere Algorithm in general.

To examine the influence of ground level meteorological data, first an initial lookup table and convergence area are generated based on the standard CCIR ground conditions:

T(0) = 15°C,
P(0) = 101.3 kPa,
RH(0) = 60%,
R(0) = 0 mm/h.

Then each time one parameter, temperature, pressure or relative humidity, is varied in certain steps and the resulting change in convergence area and lookup table are determined.

With the implementation of the Matched Atmosphere Algorithm a choice has to be made about when to switch to a new lookup table. More concrete, how much can the input parameters *T(0), P(0)* and *RH(0)* change before an other lookup table is going to be used. To make a sensible choice, the inaccuracy introduced by these steps has to be compared with the inaccuracy in vapour and liquid retrieval due to the limited accuracy in the brightness temperatures measured by the radiometer. The radiometer measures brightness temperatures with an accuracy of ±1K for both 21.3GHz and 31.7GHz, which may result in deviations in V and L of approximately ±1.5mm and ±0.05mm respectively. This automatically means a limitation on the accuracy with which the amount of water vapour and liquid water can be retrieved. The choice of how much the ground level values of *T(0), P(0)* and *RH(0)* may change, before a new look up table is going to be used must be made in such a way that the inaccuracy introduced is in the same order of magnitude. Making a finer resolution is superfluous and will only suggest a better accuracy.

6.2.1 Ground level temperature

First the influence of the ground level temperature on the convergence area has been looked at. This is done by calculating the convergence area for *T(0) = 10°C, 15°C* and *20°C* respectively. The results are shown in Figure 6.7. From this figure can be seen that, as the temperature increases, the convergence area shifts to higher values of T_{20} and T_{30} and also gets larger; it expands to higher brightness temperatures. This latter effect is caused by the cloud top increasing together with the ground level temperature, because of this the maximum cloud thickness and maximum obtainable brightness temperatures increase.

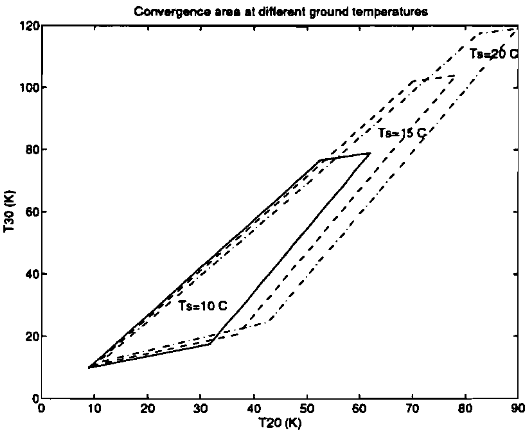


Figure 6.7 The convergence area at different ground level temperatures.

Recalling the clear sky situation in which the measured brightness temperature combinations were just outside the convergence area, we now try to find out if this could be due to an inaccuracy in ground level temperature data. The original ground level conditions for this case were: *T(0)=18°C, P(0)=101.3kPa, RH(0)=52%* and *R(0)=0mm/h*. Figure 6.8 contains a detailed picture of the edge of the convergence area for these conditions (solid line) and the measurement points. When the ground temperature value is decreased by 2 degrees to *16°C* the edge of the convergence area shifts to the position as is indicated by the dashed line. This considerable change in ground level temperature does not lead to a situation where all measurement points are within the convergence area. In practice the inaccuracy in *T(0)* is less then 2 degrees. From this can be concluded that the influence of the ground level temperature on the results is too little to appoint inaccuracies in this variable as a reason for the negative liquid water amounts.

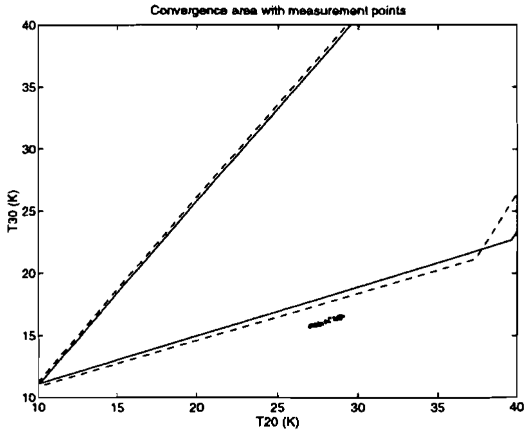


Figure 6.8 Convergence area with measurement points.

In the present implementation of the algorithm for every 2 degrees change in ground level temperature a new lookup table is being switched to. This limited resolution introduces some inaccuracy in the calculated *V* and *L* values. To get an impression about how large this inaccuracy is, lookup tables for *T(0)=13°C* and *T(0)=17°C* have been calculated. These lookup tables have been compared to the one corresponding to *T(0)=15°C* and the largest deviation in *V* and *L* have been determined. Same has been done for larger steps in *T(0)* as is shown in Table 6.1, in all cases the lookup table corresponding to *T(0)* is taken as a reference.

T(0) (°C)	ΔV_{max} *(mm)*	ΔL_{max} *(mm)*
5	*-1.497*	*+0.051*
10	*-1.092*	*+0.034*
13	*-0.431*	*+0.024*
17	*+0.537*	*-0.015*
20	*+1.588*	*-0.043*
25	*+2.602*	*-0.088*

Table 6.1 Maximal changes in V and L in relation to changes in T_s

From Table 6.1 can be concluded that when for every 2 degrees change in ground level temperature the lookup table is updated, the maximum deviation in *V* is in the order of magnitude of ±0.55mm whereas for *L* this is ±0.025mm. When these values are compared to the deviations in *V* and *L* introduced by the limited accuracy in brightness temperatures measured by the radiometer (±1.5mm for *V* and ±0.05mm for *L*) it can be seen that these are about 2 times lower. It can be concluded that temperature steps of 2°C are small enough and therefore measuring temperature with this accuracy is sufficient.

During the CLARA measurement campaigns was measured at a nearby field with an accuracy of 0.1°. The actual position of the radiometer was a few hundred meters further on, on top of a building of about 70m height. The difference in the temperature measured at the field and the actual temperature at the radiometer position is probably not more then 1°. The temperature used in calculations can therefore be considered accurate enough.

6.2.2 Ground level relative humidity

Same as with the temperature also the influence of the ground level humidity on the convergence area has been examined. This has been established by plotting the convergence area for *RH(0)=50%*, *RH(0)=60%* and *RH(0)=70%* respectively, as is shown in Figure 6.9. From this figure can be seen that the relative humidity at ground level has negligible effect on the convergence area. Therefore inaccuracy in the ground level relative humidity data is for certain not the reason for measurement points falling outside of the convergence area.

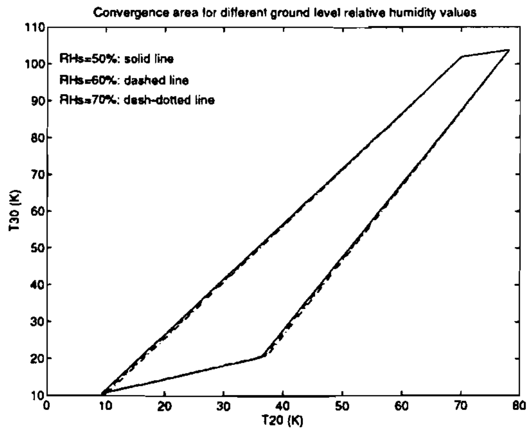


Figure 6.9 Convergence area at different ground level relative humidity values

Also with relative humidity a choice has to be made about how often the Matched Atmosphere Algorithm has to switch to a new lookup table. In the present implementation this is done whenever the relative humidity at ground level changes more then 5%. The inaccuracy introduced by this limited resolution is determined by comparing the lookup tables that correspond to *RH(0)=55%* and *RH(0)=65%* to the lookup table calculated at *RH(0) =60%* in order to find the largest differences in both *V* and *L*. In addition this has been done for differences of 10% in the ground level relative humidity. The results are shown in Table 6.2.

RH_s (%)	ΔV_{max} (mm)	ΔL_{max} (mm)
50	0.061	$4.0 \cdot 10^{-3}$
55	0.037	$2.3 \cdot 10^{-3}$
65	0.031	$2.4 \cdot 10^{-3}$
70	0.063	$4.5 \cdot 10^{-3}$

Table 6.2 Maximal changes in V and L in relation to changes in RH_s

From this table can be seen that changes in relative humidity at ground level have just a small effect on the resulting values for water vapour and liquid water amounts. When for every 5% change in ground level relative humidity the lookup table is updated, the maximum deviation in V is in the order of magnitude of 0.04mm whereas for L this is $2.4 \cdot 10^{-3}$ mm. These deviations are about 10 times smaller as those introduced by the 2 degrees resolution in temperature.

6.2.3 Ground level pressure

The ground level pressure influences the convergence area just slightly, as can be seen in Figure 6.10. In this figure the convergence areas for *P(0)=100.3kPa, P(0)=101.3kPa* and *P(0)=102.3kPa* are plotted. In spite of the considerable changes in pressure levels the difference in convergence areas can hardly be noticed, which leads to the conclusion that inaccuracy in ground pressure level can also be excluded as the reason for the negative liquid water values that are obtained.

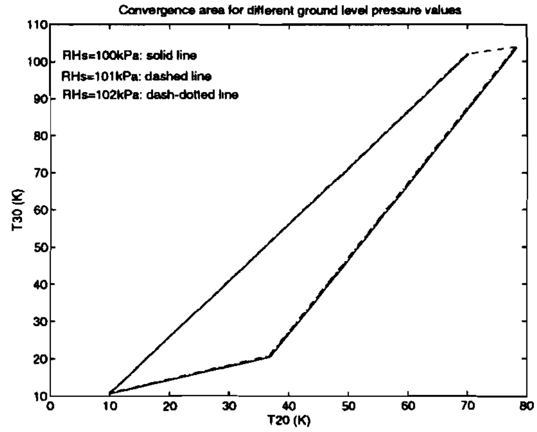


Figure 6.10 Convergence area at different ground level pressure values

To see how sensitive the Matched Atmosphere Algorithm is to changes in ground level pressure, the lookup tables for *P(0)=99.3kPa, P(0)=100.3kPa, P(0)=102.3kPa* and *P(0)=103.3kPa* were generated and compared to the one corresponding to *P(0)=101.3kPa*. The maximum changes in V and L are shown in Table 6.3. From this table can be seen that when the ground level pressure is varied over a large range, the effect that this has just a slight effect on the water vapour and liquid water values, as was expected. Not using the actual ground level pressure data in the Matched Atmosphere algorithm introduces just a small inaccuracy, when compared to the deviation introduced by the limited temperature resolution.

P_s (kPa)	ΔV_{max} (mm)	ΔL_{max} (mm)
99.3	0.35	0.063
100.3	0.18	$7.2 \cdot 10^{-3}$
102.3	0.18	$6.7 \cdot 10^{-3}$
103.3	0.81	0.044

Table 6.3 Maximal changes in V and L in relation to changes in RH_s

From the foregoing can be concluded that only the ground level temperature has a significant influence on the calculated values of V and L. The influence of the of the other ground level meteorological parameters is limited. When the resolution T, P and RH are chosen 2°, 1kPa and 5% respectively the mean variance (found by squared addition of all separate contributions) is 0.32mm for V and 0.025mm for L and therefore smaller than the deviations introduced by the inaccuracy of the brightness temperature measurements by the radiometer.

Although inaccuracy in ground temperature causes the convergence area to shift, inaccuracies in the ground level variables can not be the only reason for the measured brightness temperature combinations being outside of the convergence area. Therefore the explanation for the negative water liquid values, in case of low humidity in the atmosphere, must also be looked for in other causes for deviations between the real atmosphere and the matched profiles, or in inaccuracy in the brightness temperature measurements.

6.3 Other model parameters

There are a few other parameters in the MPM and Peter and Kämpfers atmosphere model that influence the final result of the Matched Atmosphere Algorithm. One of these parameters is the constant C from Equation 2.19 which is said to represent the cloud type. This constant can vary in the range from 0.1 to 0.7. From Equation 2.19can be seen that there is a linear relationship between C and the liquid water density. As a consequence L is also proportional to C. The constant C is only determinative for the amount of liquid in a cloud, the integrated water vapour content does not depend on C at all, as can be seen in Figure 6.11. It can also be seen that changes in C influences the brightness temperature T_{20} but not the amount of water vapour. This means that C is normative for the liquid water contribution to T_{20} .

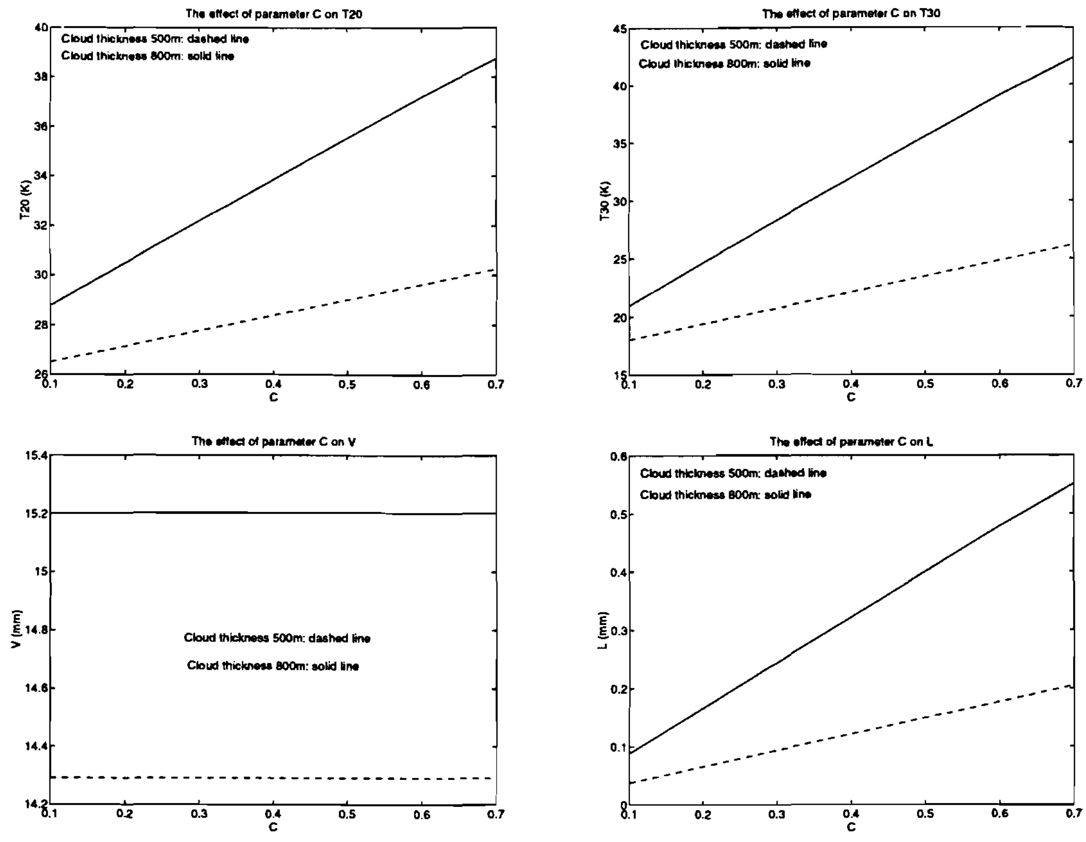


Figure 6.11 The effect of cloud type parameter C on T_{20}, T_{30}, V and L

Another parameter that has to be chosen in the Matched Atmosphere Algorithm, is the parameter C_l in Equation (2.18), which determines the concentration of aerosols. In the algorithm, as it has been implemented at the moment, C_l is set to 2.41. This corresponds to the value for an urban environment, which the city of Delft is taken to be. Same as with the other parameters in the algorithm, it was examined how changes in the value of C_l influence the results of water vapour and liquid water retrieval. This was done by calculating the look up tables for V and L with other values of C_l (namely 1.87 for a rural environment, 5.31 for a maritime environment and 5.83 for a maritime environment with strong wind) and compare them to the original look up tables (corresponding to C_l=2.41). The maximum changes in V and L found this way are shown in Table 6.4. From this table can be seen that changes in C_l have just a very small effect on the results of water vapour and liquid water retrieval. The influence is about 1000 times smaller than the inaccuracy introduced by the limited temperature resolution. Therefore C_l is not a critical parameter in the calculations of V and L.

C_l	ΔV_{max} (mm)	ΔL_{max} (mm)
1.87	$1.6 \cdot 10^{-4}$	$2.7 \cdot 10^{-5}$
5.31	$3.1 \cdot 10^{-4}$	$5.1 \cdot 10^{-5}$
5.83	$3.3 \cdot 10^{-4}$	$5.5 \cdot 10^{-5}$

Table 6.4 Maximal changes in V and L in relation to changes in C_l

6.4 Conclusions

As was shown by the plots in Appendix C, both temperature profiles and relative humidity profiles of the atmosphere are hard to estimate using only ground level meteorological data. Deviations between the matched profile and the real atmospheric profile introduce errors in the calculations of both water vapour and liquid water contents. By means of weighting functions the effect of deviations between the real and the estimated temperature and relative humidity profiles has been shown.

Because of the fact that clouds are often just underneath a temperature inversion, a better estimation about the cloud height could be made when the temperature profile is known. Improvement of the algorithm can therefore best be achieved by introducing a priori knowledge about the temperature profile in the calculations. More information about the actual temperature profile could be obtained by using measurement data of radiosondes, radio acoustic sounding or a radiometer in the 50GHz range.

Another point what has been looked is the influence of ground level meteorological data, cloud type parameter, C and parameter C_l (determining the aerosol concentration) on the results of the Matched Atmosphere algorithm. One of the objectives for this was to find an explanation for measurement point falling just outside the convergence area in case of an atmosphere with very low humidity. When reasons for this would be found, the model could be adjusted in a way that no negative liquid values are obtained anymore. It showed however that ground level values of temperature, pressure and relative humidity have just a slight influence on the calculations. Also changes in the parameter C can not resolve the negative values of liquid water contents.

It has been shown that using a new look up table whenever the ground level values of temperature changes 2°, relative humidity changes 5% and pressure changes 1kPa, this gives a good enough resolution. The inaccuracy that is introduced in the vapour and liquid retrieval this way is about 2 times smaller than those introduced by inaccuracy in the brightness temperatures measured by the radiometer.

It is suspected that the fact that measured T_{20},T_{30} combinations are sometimes just outside the convergence area is caused by deviations between the brightness temperatures calculated from a particular atmosphere and the brightness temperatures measured from that same atmosphere. The reason for this deviation could be inaccuracy in the radiometer measurements, an inaccuracy in MPM, inaccurate modelling assumptions or inaccuracy introduced by interpolation/extrapolation. To learn more about this and get insight in the accuracy of the Matched Atmosphere Algorithm, in the next chapter measurements and calculations are compared.

7. Comparing retrieval with reference values

The combination of all different instruments which gathered information about the atmosphere and clouds during the CLARA campaigns, offers the unique possibility to gain insight in the accuracy of the water vapour and liquid water retrieval algorithms. In our case we use radiosonde, lidar and radar measurements together with the measured brightness temperatures in order to be able to verify the results of the Matched Atmosphere Algorithm.

7.1 Definition of reference values

At times that a radiosonde is launched, the temperature, relative humidity and pressure profiles of the atmosphere are known. From these profiles the integrated water vapour content of the atmosphere can be calculated directly, using Equations 2.12 and 2.15. The amount of water vapour found this way can be used as a reference in the comparison with the amount of water vapour found by the Matched Atmosphere Algorithm.

In no cloud conditions the integrated liquid water content is 0 and the brightness temperatures at 21.3GHz and 31.7GHz can be calculated from the radiosonde profiles using the MPM. These values of T_{20} and T_{30} are compared with those measured by the radiometer. As has been seen earlier, the liquid water content obtained with the Matched Atmosphere Algorithm is not always equal to zero, therefore in the comparison of these liquid water values with the theoretical value, *L=0mm*, the negative values in no cloud conditions are suspicious.

When clouds are present there is a increase in liquid water content which in turn gives a contribution to both T_{20} and T_{30}. Since the integrated liquid water content is not measured, nor can be calculated directly from other measurements yet, there is no real reference to verify the values found for this quantity by the Matched Atmosphere Algorithm. The best possible way to calculate the integrated liquid water content at the moment, is to use the radiosonde profiles of *T, P* and *RH* together with the cloud height information derived from lidar and radar. When the cloud height is known, a cloud can be introduced as is done in the MPM according to Equation 2.19. Using this method implies that assumptions about cloud characteristics are made, and therefore influences the accuracy of the comparison of measured and calculated liquid water contents and brightness temperatures. Maybe in a later stage more information about cloud characteristics can be retrieved from radar data and this way a better reference can be obtained. The integrated water vapour content can also in clouded conditions be directly calculated from radiosonde profiles. Comparing these values with the water vapour amounts obtained with the Matched Atmosphere Algorithm is therefore possible.

The accuracy of the comparison furthermore depends on:

- the accuracy of the radiosonde data which is:
  - ±1°C in temperature
  - ±0.1kPa in pressure
  - ±10% to 15% in relative humidity
- the accuracy of the RESCOM radiometer which is specified to be:
  - ±1K in brightness temperature at 21.7GHz
  - ±1K in brightness temperature at 31.7GHz.

7.2 Results

Comparisons of calculated amounts of water vapour and liquid water with the corresponding reference values were performed for the first and the second CLARA measurement campaign separately. It must be noted that, when there is a difference of more than 4K between the calculated brightness temperature and measured brightness temperature at either measurement frequency, the observation is excluded from the comparison because it is not reliable. The reason for such deviations can be found in fog or rain which are not taken into account in the model used for calculations, or significant changes in the atmosphere during the time that the radiosonde is measuring the profiles (for instance a transition from a clear sky situation to clouded conditions).

7.2.1 First CLARA measurement campaign

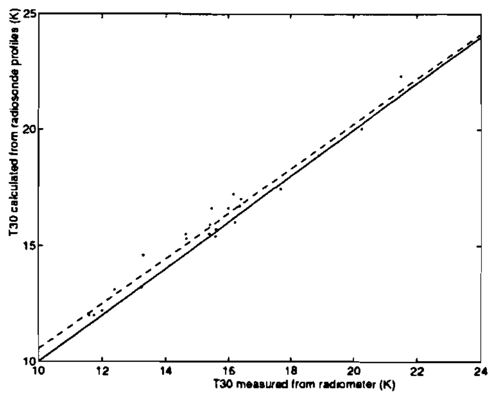
The results of the comparisons of the first CLARA measurement campaign, which was from April 15th to April 26th 1996, are shown in Figure 7.1. Table 7.1 contains significant features of the comparison.

	Slope	*Intercept*	*Bias (meas-calc)*	*RMS difference*
T_{20} *comparison*	*0.85*	*2.89*	*0.95 K*	*1.75 K*
T_{30} *comparison*	*0.97*	*0.86*	*-0.39 K*	*0.59 K*
V comparison	*0.77*	*0.49*	*2.85 mm*	*3.21 mm*
L comparison	-	-	*-0.02 mm*	*0.03mm*

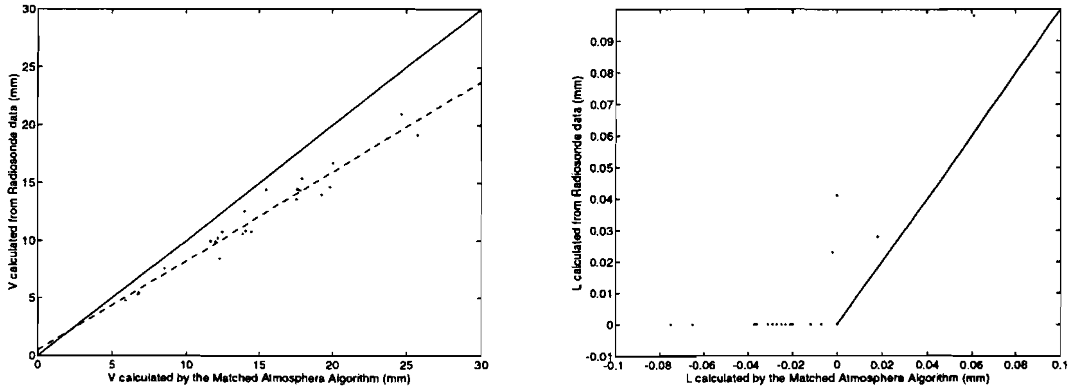
Total number of observation points: 23

Table 7.1 Features in the comparison of measured and calculated quantities.

The most accurate comparison can be done with the water vapour content, because here the assumptions on cloud modelling have no influence. It can be seen that the integrated water vapour contents calculated by the Matched Atmosphere Algorithm is in all cases larger than that calculated from the radiosonde profiles. A possible reason for this is an inaccuracy of the brightness temperatures measured by the radiometer.



Comparison of measured and calculated brightness temperatures at 21.3GHz and 31.7GHz



Comparison of V and L calculated from radiosonde data and calculated by the Matched Atmosphere Algorithm
Solid line is 45°, dashed line is determined by regression.

Figure 7.1 Comparison for the first CLARA measurement campaign

7.2.2 Possible reasons for the difference in retrieval results.

There are a number of reasons which can be appointed for the deviation between the brightness temperatures calculated from radiosonde profiles, and values measured by the radiometer. Same goes for the differences between the water vapour and liquid water amounts retrieved by the Matched Atmosphere Algorithm and the corresponding reference values obtained. The possible reasons for the deviations are described in this section.

7.2.2.1 Inaccuracy brightness temperature measurements

When the measured brightness temperature at 21.3GHz is too high and/or the measured brightness temperature at 31.7GHz is too low, the water vapour values calculated with the Matched Atmosphere Algorithm that will be too high. Judging from the graphs in Figure 7.1, where measured brightness temperatures are compared to those calculated from radiosonde data this deviation could be the case, because T_{20} tends to be too high whereas T_{30} is in most cases too low. The inaccuracy in T_{20} seems to increase with larger brightness temperature values, for inaccuracies in T_{30} this is not the case. The accuracy of the brightness temperature measurements of the radiometer is specified to be ±1K.

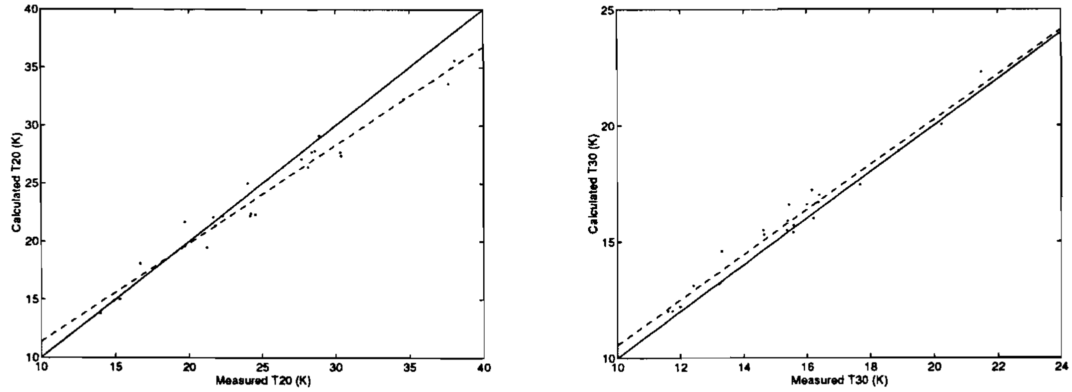


Figure 7.2 Shifted measurement points (T_{20}-1K, T_{30}+1K) with convergence area in clear sky conditions and with thin cloud respectively.

To see what improvement in water vapour retrieval can be obtained when the brightness temperature combinations, used as input for the Matched Atmosphere Algorithm, are shifted within this margin, calculations were carried out with all T_{20} values decreased by 1K and all T_{30} values increased by 1K. This way the measurement points agree better with the calculated values, also points that are outside the convergence area (Figure 6.6) come to lie closer to the edge or just within as shown in Figure 7.2.

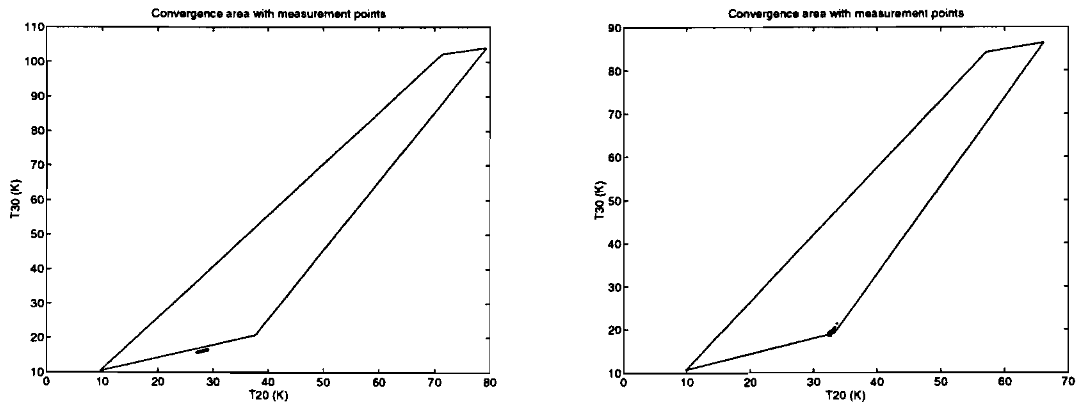
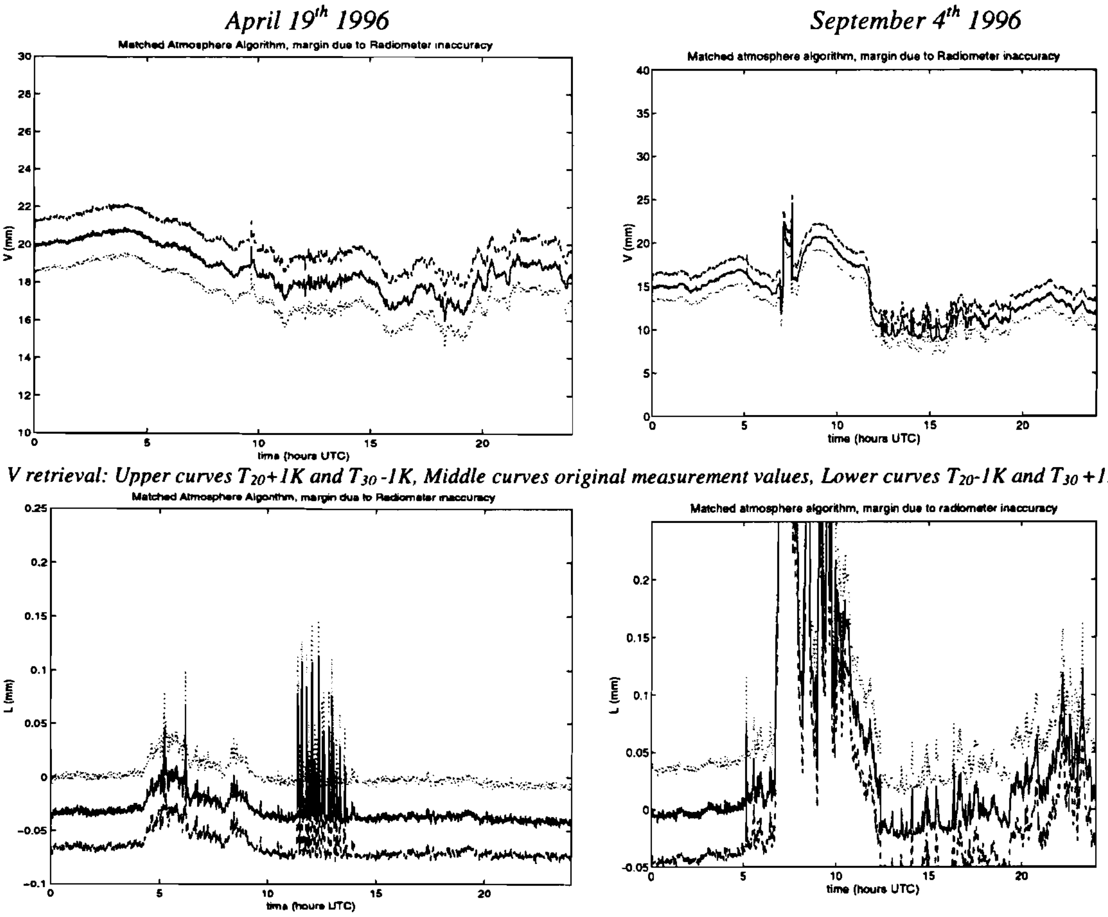


Figure 7.2 Convergence area with 'shifted' measurement points in clear sky conditions and with thin clouds respectively.

To illustrate the effect of shifting the measurement points within the margin of the radiometer accuracy has, the minimum and maximum amounts of water vapour and water liquid that can be obtained, are shown together with the original curves, in Figure 7.3. This was done for both April 19th and September 4th, 1996.

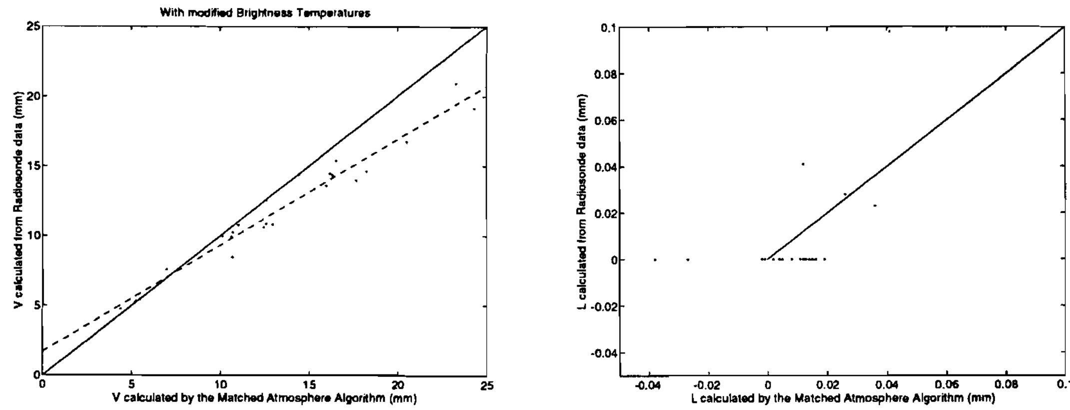


V retrieval: Upper curves T_{20}+1K and T_{30} -1K, Middle curves original measurement values, Lower curves T_{20}-1K and T_{30} +1K.

L retrieval: Lower curves T_{20}+1K and T_{30} -1K, Middle curves original measurement values, Upper curves T_{20}-1K and T_{30} +1K.

Figure 7.3 Maximum and minimum values of V and L obtained when shifting the T_{20}, T_{30} within the radiometer accuracy margin

When for this case the integrated water vapour contents values obtained with the Matched Atmosphere Algorithm are compared to those calculated from radiosonde profiles, this results in the picture of Figure 7.4. Here the rms difference is 2.14mm which is considerably less than with the original measurement data. From this can be concluded that inaccuracy in measured brightness temperature can be a reason for the deviation between the water vapour values calculated by the Matched Atmosphere Algorithm and those calculated from radiosonde profile. Also can be seen that shifting of the measurement points result in less negative values for the liquid water content calculated by the Matched Atmosphere Algorithm, which is an improvement too.



T_{20} measurement points decreased by 1K, T_{30} measurement points increased by 1K,
Solid line is 45°, dashed line is determined by regression.

Figure 7.4 Comparison of V and L calculated by the Matched Atmosphere Algorithm reference values.

7.2.2.2 Measurement inaccuracy of the radiosondes

Another possible reason for this deviation is the inaccuracy in the radiosonde measurements of atmospheric profiles. The accuracy at which the sensors of radiosondes measure temperature, pressure and relative humidity were mentioned in Section 7.1. When these accuracies are taken into account in the calculations of water vapour contents from radiosonde profiles, it shows that there is an uncertainty of about ±18% in the obtained values, which is illustrated in Figure 7.5. From this picture can be seen that the water vapour values calculated from radiosonde data are no exact reference points and therefore verification of the accuracy of water vapour retrieval algorithms can only be done to a limited extent.

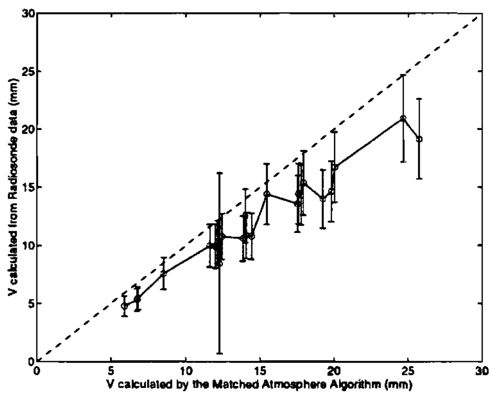


Figure 7.5 Comparison of V calculated by the Matched Atmosphere Algorithm with V calculated from radiosonde profiles with the uncertainty introduced by the limited accuracy in the radiosonde profile data.

7.2.2.3 In accuracy in MPM

A final reason for the deviation between *V* calculated by the radiosonde and *V* obtained with the Matched Atmosphere Algorithm could be an inaccuracy in the absorption model MPM. In a similar experiment, performed by Westwater [10], brightness temperatures calculated from radiosonde profiles were compared to values measured by a radiometer. With this experiment only radiosonde launches under clear sky conditions were taken into account, this way there is no influence of cloud liquid modelling introduced in the results. From the comparison of the calculated brightness temperatures with the measured values, Westwater found a rms difference of 2.91K and a bias of 2.51K in T_{20} and a rms difference of 1.26K and a bias of 1.032K in T_{30} using a set of 112 observation points. These results are comparable to what we find from the data of the CLARA campaigns.

In another comparison that is Westwater carried out, he compares the brightness temperatures measured in both channels to brightness calculated from radiosonde profiles using the microwave propagation model developed by Waters [15]. In this comparison he finds a better agreement between the measured and the calculated brightness temperatures in the 20GHz as well as the 30GHz range. With this Westwater suggests that the microwave propagation model by Waters is more accurate in the 20/30GHz range than Liebes MPM. If this is indeed the case or if the previous observation applies only for this particular case can not be established.

What finally can be seen from the liquid water comparison plot of Figure 7.1, is that the liquid water amounts are very low, which agrees with the low humidity in the atmosphere during the measurement campaign. Furthermore it shows that the rms difference between the liquid water contents calculated with the Matched Atmosphere Algorithm of 0.03mm is in the same order of magnitude as the *L* values. This results in large inaccuracies expressed in percentage.

7.2.3 Second CLARA measurement campaign

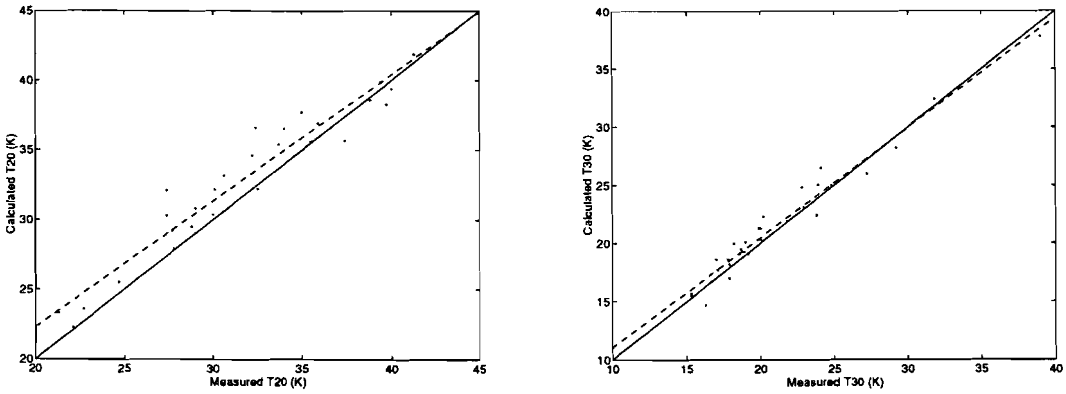
The same comparison was done for the second CLARA measurement campaign, which took place from August 19th until September 4th 1996. Features of this comparison are shown in Table 7.2 and Figure 7.6.

	Slope	*Intercept*	*Bias (meas-calc)*	*RMS difference*
T_{20} *comparison*	*0.91*	*4.18*	*-1.19 K*	*1.89 K*
T_{30} *comparison*	*0.95*	*1.56*	*-0.43 K*	*1.13 K*
V comparison	*0.89*	*2.35*	*0.38 mm*	*1.22 mm*
L comparison	-	-	*-0.02 mm*	*0.04mm*

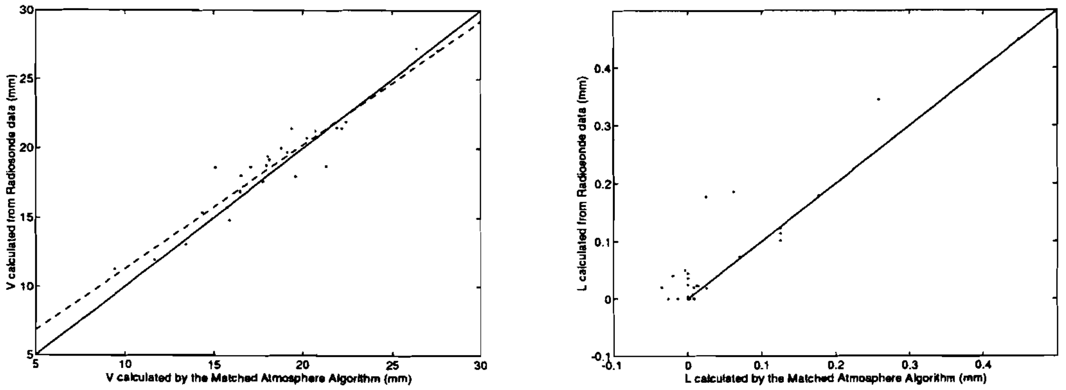
Total number of observation points: 30

Table 7.2 Features in the comparison of measured and calculated quantities.

At the time this report was written, no lidar or radar data for the second measurement campaign was available. Therefore the cloud base height and cloud top height were estimated from the radiosonde temperature and dewpoint temperature profiles, as was described in Section 4.4.2. This may be a reason for the larger rms differences in measured and calculated brightness temperatures.



Comparison of measured and calculated brightness temperatures at 21.3GHz and 31.7GHz



Comparison of V and L calculated from radiosonde data and calculated by the Matched Atmosphere Algorithm
Solid line is 45°, dashed line is determined by regression.

Figure 7.6 Comparison for the second CLARA measurement campaign

For the comparison of the integrated water vapour contents calculated by the Matched Atmosphere Algorithm and from radiosonde data the cloud estimation has no influence. Here it can be seen that rms difference is only 1.22mm, which is considerably less than for the data of the first CLARA campaign. Also can be seen that there is a much smaller bias, which in this case is -0.3833mm where for the first CLARA campaign this was 2.85mm. Thus the water vapour contents calculated with the Matched Atmosphere Algorithm for the second measurement campaign are in general a bit too low.

From Figure 7.5 can be seen that the Matched Atmosphere Algorithm still gives negative liquid water amounts now and then. These points result from clear sky periods which were present during the second measurement campaign. Furthermore it can be seen that for larger liquid water amounts the values agree quite well. However, one has to keep in mind the fact that the same cloud modelling assumptions were used in both radiosonde calculations and Matched Atmosphere Algorithm may have influence on this comparison.

A last thing that can be noted for the first as well as the second measurement campaign, is that in both cases the brightness temperature comparison at 31.7GHz shows a much better correspondence than that at 21.3GHz (less rms difference and points are closer to the theoretical 45° line). This is in accordance with what was expected on the basis of the weighting functions Figure 6.2, which show that the brightness temperature at 31.7GHz is less sensitive to deviation between the matched and the actual atmospheric profiles of temperature and relative humidity, than the brightness temperature at 21.3GHz.

7.3 Conclusions

In this chapter it has been shown that the retrieval of the integrated water vapour content from radiometer measured brightness temperatures, using the Matched Atmosphere Algorithm gives results that agree quite well with the values obtained from radiosonde data. For the first CLARA measurement campaign the rms difference was 3.21mm, whereas for the second campaign this was 1.22mm. The derivations that are found are comparable to the results of a similar experiment carried out by Westwater [10], where only observations under clear sky conditions were used in the examinations.

For water liquid amounts there is no real reference that can be used for verification. By using the cloud modelling according to Liebe together with radiosonde profiles and lidar or radar cloud height information a reference for the liquid water content is defined. When these values are used in the comparison with the liquid water contents calculated by the Matched Atmosphere Algorithm, this results in a good correspondence. But because in both liquid water calculations the same cloud modelling assumptions are used, it may be questionable if this method of comparing is valid. It would be desirable to get another reference for the water liquid amounts, for instance calculated FSSP.

The deviations found in the comparison of brightness temperatures, water vapour contents and liquid water values is due to a combination of the reasons:

- Deviation between the profiles used by the Matched Atmosphere Algorithm and the actual atmosphere. This is clearly indicated by the deviations in brightness temperatures, which are larger at 21.3GHz than at 31.7GHz, as was expected from the weighting functions of temperature and relative humidity in Figure 6.2.
- Inaccuracy in the brightness temperatures measured by the radiometer. This might have been the case in the first CLARA measurement campaign, as shown in Section 7.1 (Figure 7.2).
- Inaccuracy in the calculation of brightness temperatures by the MPM, as was suggested by Westwater in [10].
- Inaccuracy in the reference values. The references used in the comparison are obtained from radiosonde data, in which especially the limited accuracy of the relative humidity measurement introduces errors.
- Inaccuracy introduced by the linear interpolation and extrapolation.

In order to be able to make a real statement about the accuracy of the water vapour and liquid water retrieval using the Matched Atmosphere Algorithm, a comparison containing a much larger number of radiosondes should be carried out. By comparing the brightness temperatures and water vapour amounts for clear sky conditions separately, the cloud modelling has no influence and an accurate comparison is guaranteed. This may be done in a long term experiment where radiometer, radiosondes and lidar or radar measurements are carried out.

8. Final conclusions and recommendations

In this report two types of retrieval algorithms to extract integrated water vapour V and integrated liquid water contents L from radiometer measurements were described, namely linear algorithms and matched atmosphere algorithms. Both types of algorithms show an increase in liquid water amounts whenever there is a cloud, and thus manage to detect clouds well.

The curves of water vapour and water liquid retrieval obtained with the different algorithms have all about the same shape but differ in level and range. All algorithms give negative values for the retrieved amount of liquid water during clear sky periods, which is of course physically impossible. One main reason for the differences in linear algorithms and the obtained negative L values are, that the parameters used in these type of algorithms are tuned by means of statistical methods for one specific test-site. The results obtained by means of linear algorithms could be improved when the parameters are tuned for the specific test-site here in the Netherlands. Another reason for the negative liquid water values that are obtained, is that the assumption of a linear relation between attenuation and V and L does not hold in clear sky conditions.

Furthermore it has been shown that the SIGMA algorithms give variations in the retrieved amount of liquid water in clear sky conditions. These variations are due to a too large sensitivity of the L retrieval for changes in the brightness temperature at 31.7GHz. It is therefore recommended not to use the SIGMA-A and SIGMA-B algorithms for liquid water retrieval.

The Matched Atmosphere Algorithm is more flexible, and makes an estimation of the atmosphere based on actual meteorological measurements of temperature, relative humidity and pressure at ground level. Because of this it is expected that the Matched Atmosphere Algorithm gives more accurate results than the linear algorithms and, if necessary, adjustments in the modelling of the atmosphere can be made or additional information can be used, to get better results.

During the CLARA measurement campaigns a lot of information was gathered about the atmosphere and clouds in particular. This was done by different instruments as radar, lidar, radiometer, FSSP, radiosondes and a ground level meteostation. From the atmospheric profiles measured by radiosondes the amount of water vapour can be calculated directly. The values obtained this way are used as a reference in the comparison of the results of the other algorithm. However one has to keep in mind that these are no absolute reference values, because of the limited accuracy of the radiosonde profiles. For the integrated amount of liquid water in the atmosphere there is no real reference. By using radiosonde profiles together with radar and lidar cloud height and Liebes cloud modelling assumptions a reference was defined. When comparing the results obtained with the Matched Atmosphere Algorithm it shows that there are deviations in water vapour of up to 7.5mm. Furthermore it was noted that also the Matched Atmosphere Algorithm gives negative water liquid values during periods of clear sky.

The deviations between the water vapour and liquid water contents obtained from radiosonde data and those calculated by the Matched Atmosphere Algorithm can be due to a number of reasons. First are differences between the estimated profiles and the actual atmosphere. Especially deviations between the matched an the real temperature profiles cause considerable errors. More accurate results can be obtained when the modelled temperature profile agrees with the real atmospheric profiles better. This can be achieved by introducing more a priori knowledge of the temperature profile, for instance by using temperature reference points at different heights from measurement data of a 50GHz radiometer, as is worked on at the moment. Temperature profile could also be measured, using radio acoustic sounding. Another way to get better estimations of the atmospheric profiles could be found in using some type of interpolation between the profiles measured by consecutive radiosondes. Methods like this are used in weather forecast.

In the Matched Atmosphere Algorithm as it is implemented at this moment, the height of the cloud top is taken to be at the 0°C level. As was seen from radiosonde profiles this is often not the case. In reality the cloud is often just underneath a temperature inversion. If the height of these temperature inversions could be measured, which is possible with a radio acoustic sounder, introducing these values in the Matched Atmosphere Algorithm would given an improvement in the results.

Another reason for the deviations could be in the inaccuracy in the brightness temperatures measured with the radiometer. From the specifications of the radiometer can be seen that the brightness temperatures are measured with an accuracy of ±1K. It has been shown that, by shifting the measurement points within this range, a considerable improvement can be obtained in the vapour and liquid results of the first measurement campaign.

The deviations could also be due to inaccuracies in the calculation of brightness temperatures by the MPM. In [10] Westwater describes a similar experiment and suggests that there is an inaccuracy in the brightness temperatures calculated by Liebes MPM. Whether this is really the case can not be confirmed.

Finally inaccuracy introduced by linear interpolation and extrapolation in the Matched Atmosphere Algorithm attributed to the deviations between the calculated water vapour and liquid water values calculated by the Matched Atmosphere Algorithm and the reference values calculated from radiosonde and lidar data. What the exact influence of this linear interpolation and extrapolation is, is one of the points that must be looked closer at in future.

Which of the previously mentioned reasons is responsible for the deviations and to what extent is hard to say, probably it is a combination of all. Another point is that the reference points used in the comparison are not exact either, due to the limited measurement accuracy of the radiometer sensors, especially the relative humidity sensor.

To get more insight in the accuracy of integrated water vapour and liquid water amounts calculated from radiometer measurement data by the Matched Atmosphere Algorithm, it is recommendable to carry out a comparison with a much larger number of radiosondes. This could be done in a long term experiment where radiometer, lidar/radar and radiosondes are included.

In the comparison of the water vapour and liquid water contents calculated by the Matched Atmosphere Algorithm with the reference values obtained from radiosonde and lidar measurements, it has been seen that the rms difference in V for the first measurement campaign was 3.21mm, whereas for the second measurement campaign this was 1.22mm. For liquid water amounts this was 0.012mm and 0.045mm respectively. This gives some indication of the accuracy of the algorithm.

The present implementation of the Matched Atmosphere Algorithm has its limitations. It is not suitable to calculate water vapour and liquid water contents in case of fog or rain. Another point is that it can handle only one cloud layer. In reality there are situations in which there are more cloud layers present at different heights. In such cases the Matched Atmosphere Algorithm models these clouds as being one layer. This results in a cloud with a cloud top at the 0°C level and with a thickness which results in equivalent values for the brightness temperatures at 21.3GHz and 31.7GHz. This modelling in one cloud layer will result in a deviation in vapour and liquid values. Maybe in future the algorithm can be improved, so it can also handle the situations as named above.

Furthermore it would be desirable to get to know more about the parameter *C*, which is used in the calculation of the liquid water density profile (Equation 2.19). This parameter is set to a fixed value of 0.4 (in the middle of its possible range, from 0.1 to 0.7), but in fact depends on the cloud type. Maybe it would be possible to make a better estimation of this parameter, making use of some cloud classification, in order to get more accurate result for liquid water retrieval.

Till now the atmosphere has been divided in layers of 100m, which are taken to be homogeneous in calculations. What influence this choice of resolution has on the accuracy of water vapour and liquid water retrieval by the Matched Atmosphere Algorithm, is an interesting point to take a closer look at.

Finally it must be remarked that, with the so-called 'adaptive linear algorithm' results in the retrieval of water vapour and liquid water are obtained that agree with the values obtained with the regular Matched Atmosphere Algorithm quite well. For the vapour curve the only difference is in a slight difference in the absolute level. For the retrieval of liquid water some more deviations can be seen, mainly for low values of *L*, which indicates that the assumption of a linear relation between *V*, *L* and the attenuation does not hold in clear sky conditions. It can be concluded that the adaptive linear algorithm, which can be used for real-time data processing and only requires a relatively limited amount of disk-space, is useful to get an impression about the amount of water vapour and liquid water in the atmosphere.

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Appendix A:
Parameters used in the linear algorithms.

T eff

	North 31.65	North 23.8	North 21.3	South 31.65	South 23.8	South 21.3
a1	0.9390	0.9476	0.9468	0.9367	0.9472	0.9465
a2	0.0012	0.0012	0.0013	0.0012	0.0012	0.0013

WATER - VAPOUR*** SIGMA A ***

	North 23.8/31.65	North 21.3/31.65	South 23.8/31.65	South 21.3/31.65
Ceff	152.300000	98.120000	150.200000	96.440000
a1	0.000240	-0.000290	0.000710	0.001100
a2	0.001300	0.002900	0.000850	0.001400
a3	-0.235000	-0.333000	-0.128000	-0.158000
P_avg	996.000000	996.000000	971.000000	971.000000
T_avg	281.000000	281.000000	287.000000	287.000000
X_avg	0.084400	0.131000	0.109000	0.170000

WATER - VAPOUR*** SIGMA B ***

	North 23.8/31.65	North 21.3/31.65	South 23.8/31.65	South 21.3/31.65
Ceff	153.600000	97.890000	155.500000	101.800000
b1	-0.005600	-0.009700	-0.004900	-0.007200
b2	-0.013000	-0.026000	-0.006800	-0.011000
b3	-0.222000	-0.307000	-0.120000	-0.143000
b4	-0.000063	0.000033	-0.000089	-0.000140
X_avg	0.084400	0.131000	0.109000	0.170000

WATER - VAPOUR*** CCIR ***

	North 23.8/31.65	North 21.3/31.65	South 23.8/31.65	South 21.3/31.65
d0	-266.560000	-274.780000	-266.560000	-274.780000
d1	0.572900	0.460100	0.572900	0.460100
d2	-0.000900	-0.002100	-0.000900	-0.002100

WATER - LIQUID*** SIGMA A ***

	North 23.8/31.65	North 21.3/31.65	South 23.8/31.65	South 21.3/31.65
a0	1.345900	1.304200	0.422500	0.471100
a1	-0.001100	-0.001100	-0.000340	-0.000370
a2	-0.001500	-0.001400	-0.000870	-0.000930
a3	4.556000	4.520000	5.336000	5.041000
a4	-0.301000	-0.290000	-1.409000	-1.107000

WATER - LIQUID*** SIGMA B ***

	North 23.8/31.65	North 21.3/31.65	South 23.8/31.65	South 21.3/31.65
b0	-0.231200	-0.228100	-0.159400	-0.162400
b1	0.003200	0.002700	-0.002400	-0.002100
b2	0.025000	0.024000	-0.003800	-0.003300
b3	4.512000	4.489000	5.511000	5.160000
b4	-0.225000	-0.222000	-1.683000	-1.326000
b5	0.000260	0.000250	0.000048	0.000053

WATER - LIQUID*** CCIR ***

	North		South	
	23.8/31.65	21.3/31.65	23.8/31.65	21.3/31.65
d0	2.954400	3.042900	2.954400	3.042900
d1	2.436000	2.269000	2.436000	2.269000
d2	0.052700	0.050000	0.052700	0.050000

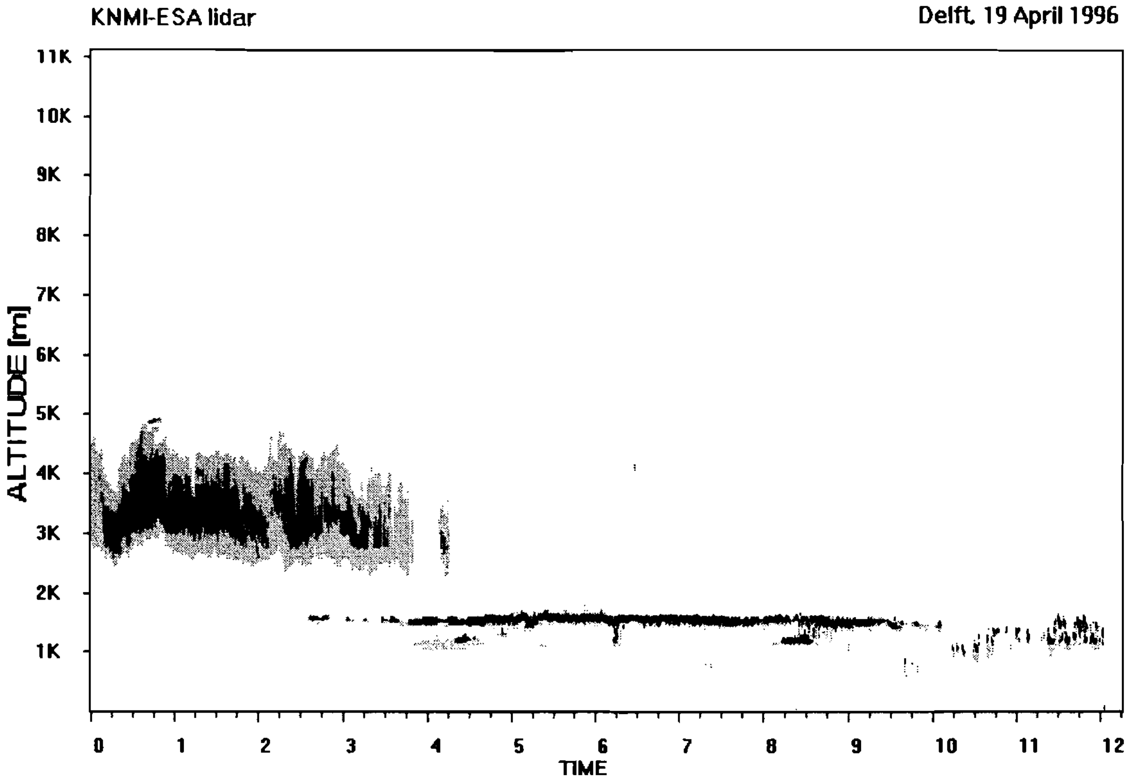
WET DELAY*** SIGMA A ***

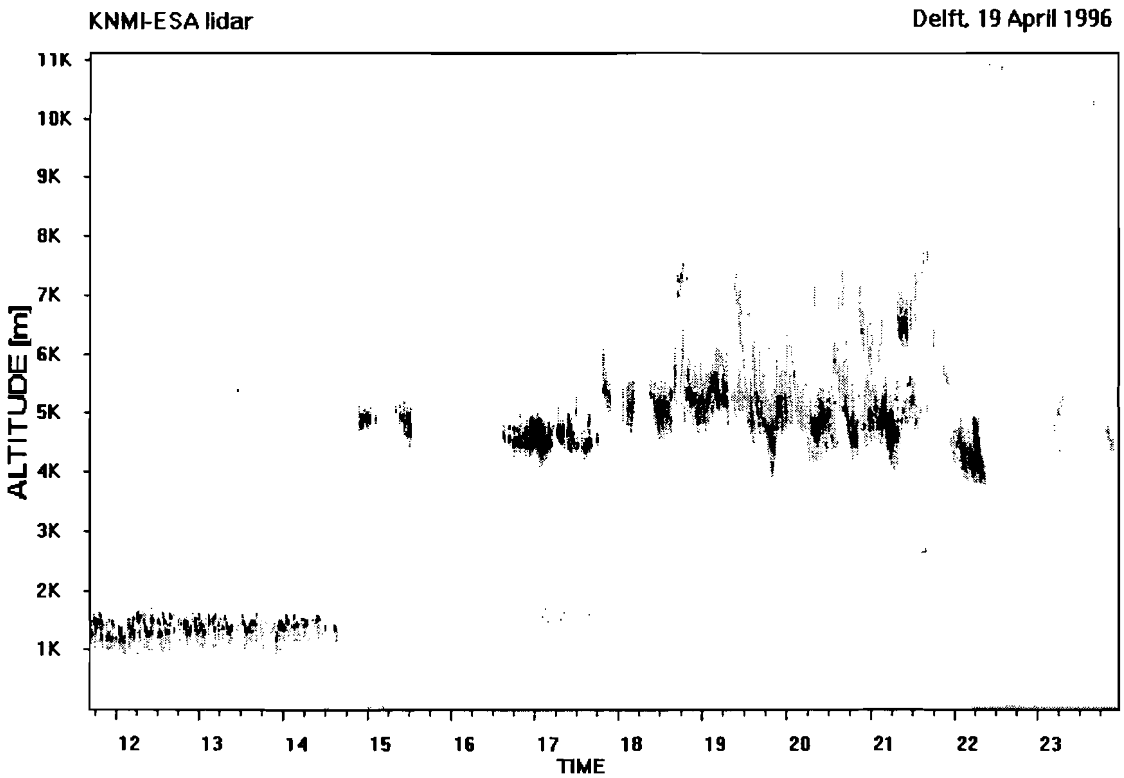
	North		South	
	23.8/31.65	21.3/31.65	23.8/31.65	21.3/31.65
Ceff	99.670000	64.190000	96.750000	62.120000
a1	0.000290	-0.000220	0.000590	0.000980
a2	-0.001200	0.000330	-0.001900	-0.001400
a3	-0.242000	-0.325000	-0.107000	-0.141000
P_avg	996.000000	996.000000	971.000000	971.000000
T_avg	281.000000	281.000000	287.000000	287.000000
X_avg	0.084400	0.131000	0.109000	0.170000

WET DELAY*** SIGMA B ***

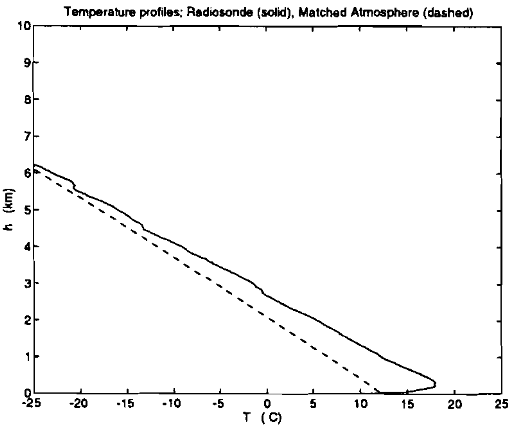
	North		South	
	23.8/31.65	21.3/31.65	23.8/31.65	21.3/31.65
Ceff	100.300000	63.910000	98.630000	64.560000
b1	0.000900	-0.002700	0.008300	0.006000
b2	0.006800	-0.004600	0.010000	0.006200
b3	-0.289000	-0.334000	-0.182000	-0.176000
b4	-0.000062	0.000033	-0.000052	-0.000100
X_avg	0.084400	0.131000	0.109000	0.170000

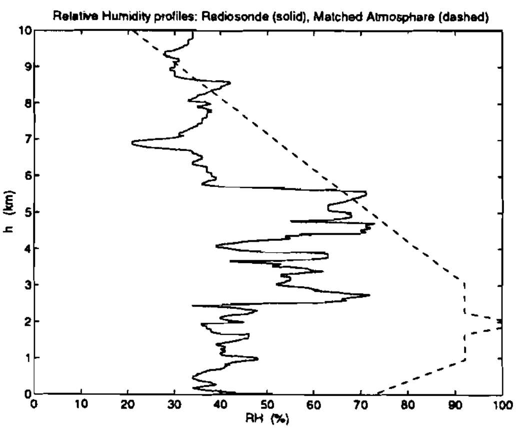
Appendix B: Lidar measurements, April 19th 1996.

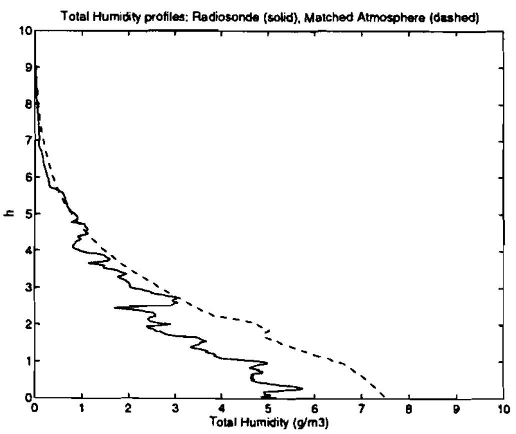




Appendix C: T, RH and Total Humidity profiles.







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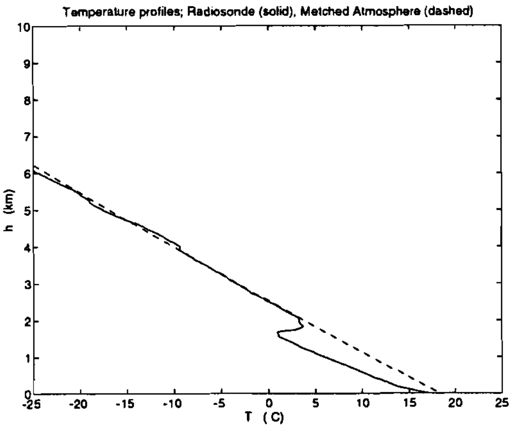

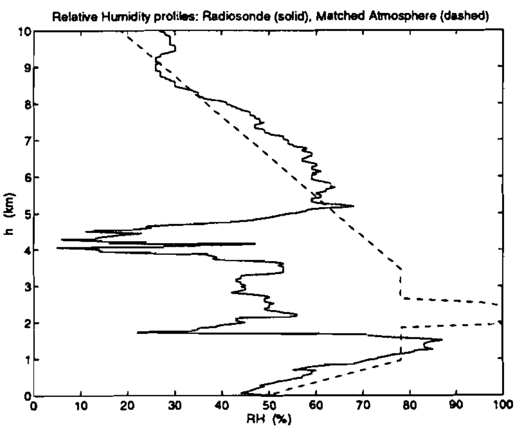

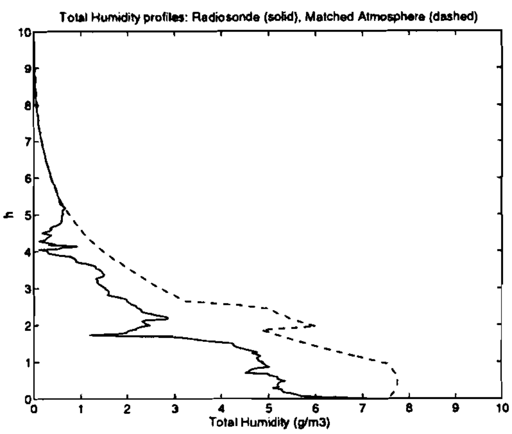

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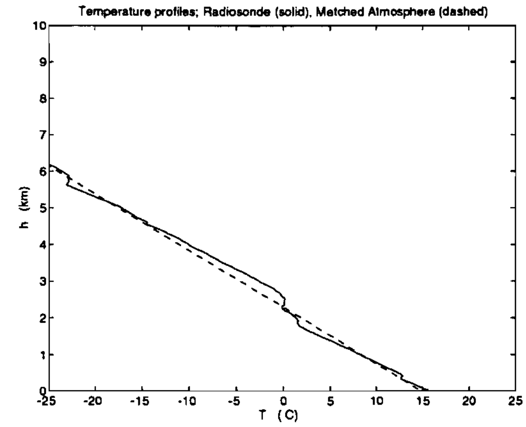

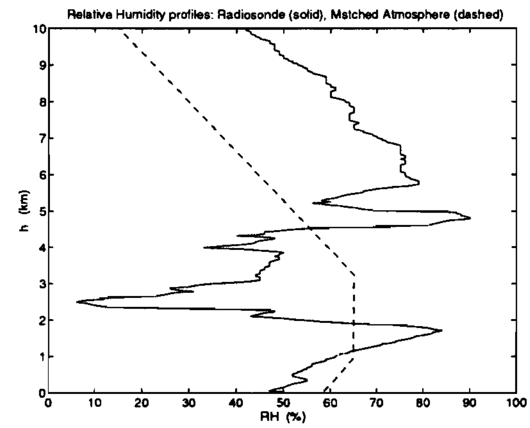

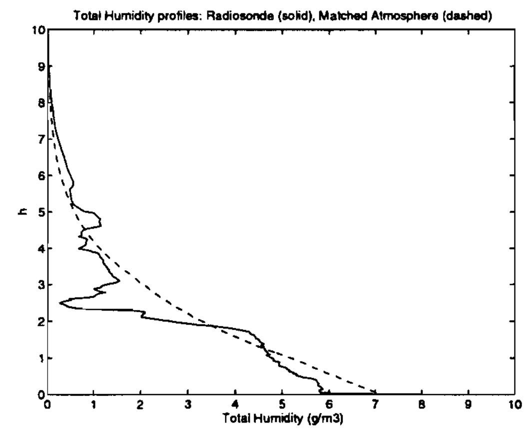

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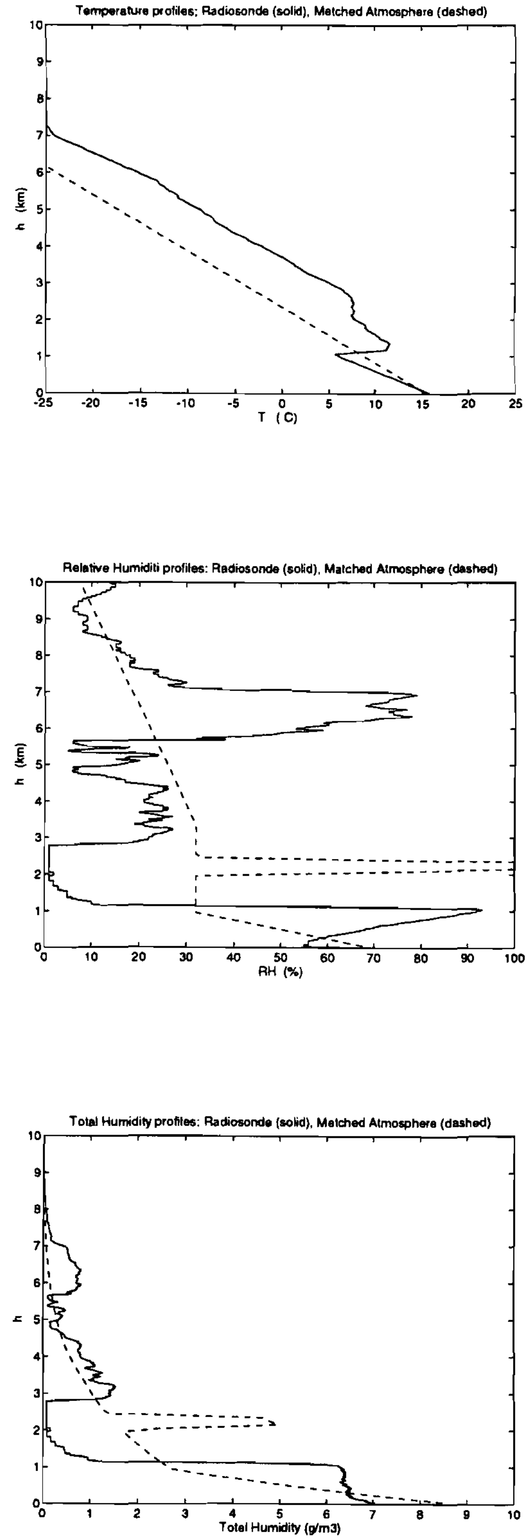

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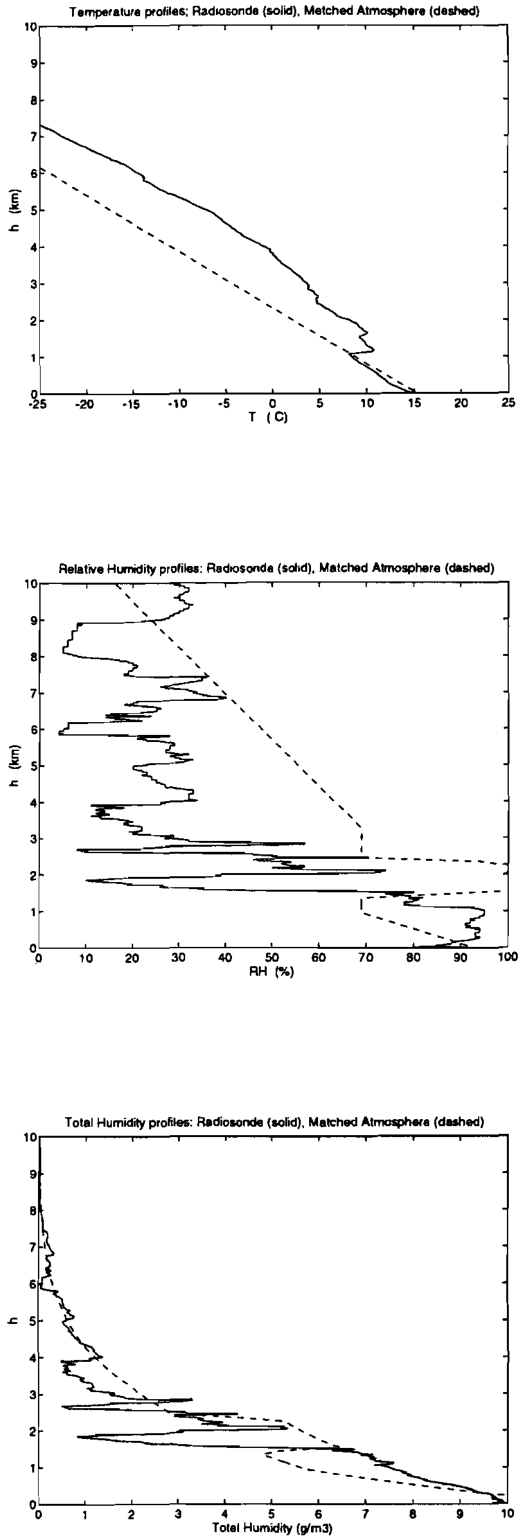

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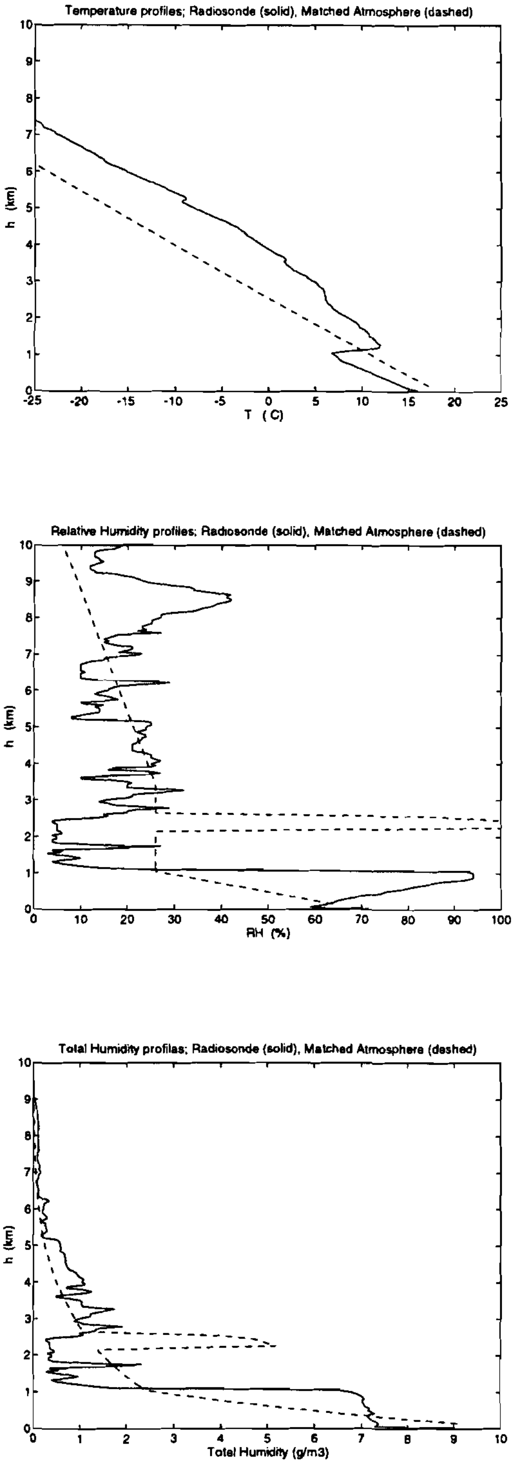

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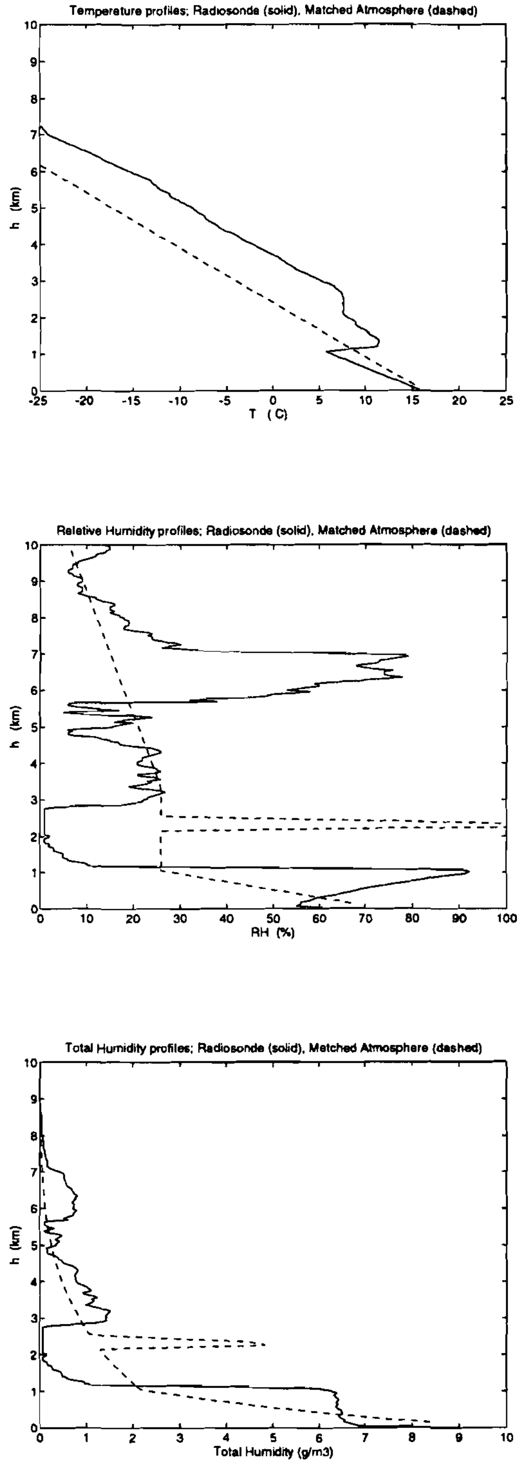

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