Temperature corrections on radiation measurements using Modtran 3

D.A. Bunskek, A.C.A.P. van Lammeren and A.J. Feijt
De Bilt, 1997

PO Box 201
3730 AE De Bilt
Wilhelmina laan 10
De Bilt
The Netherlands
Telephone +31(0)30-220 69 11
Telefax +31 (0)30-221 04 07

Authors: D.A. Bunskoek, A.C.A.P. van Lammeren and
A.J. Feijt

UDC: 551.501.721
551.501.724
551.501.776
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Temperature Corrections on Radiation Measurements using Modtran 3

D.A. Bunkseck, A.C.A.P. van Lameren and A.J. Feijt
Abstract

Temperature Corrections on Radiation Measurements using Modtran 3

Temperatures obtained from radiation measurements on clouds need to be corrected for the radiative properties of the atmospheric layer between the clouds and the sensor. This can be done using the radiative transport model Modtran 3. In order to simplify and automate the use of this model, an interface has been developed. This interface uses radiosonde data to parameterize the atmosphere, and calculates a correction table for radiation measurements. A number of cases were analysed.

It was concluded, that using this correction, a better cloud description is obtained, because of a more accurate estimate of the cloud base and top temperatures and hence the cloud base height.

Furthermore, it is now possible to use Modtran 3 routinely for temperature corrections on radiation measurements.
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1. Introduction

Weather and climate models which are used to predict and/or describe the weather rely on several parameters; for example pressure, temperature and relative humidity. The parameterization of clouds is one of the weakest components of current weather and climate models, although clouds play a very important role in our present climate. The fact that clouds are not properly parameterized is among other reasons due to our limited knowledge of clouds and their interaction with radiation.

Two important cloud parameters are the base and the top temperature. By measuring the radiance from a cloud in the so called ‘atmospheric window’, a wavelength interval from 8 to 11 μm, one can determine these temperatures.

Because clouds behave very much like blackbodies in the atmospheric window, one can use Planck’s law to calculate the cloud temperature from the measured radiance. However, there is always an atmospheric layer between the sensor and the cloud. This layer influences the radiative measurements. In order to derive the correct temperature from the radiative measurements a correction has to be made.

To determine the radiative properties of the part of the atmosphere between the sensor and the cloud, the radiative transport model Modtran 3 is used. Modtran 3 has to be ‘fed’ with parameters like pressure, temperature and relative humidity at several heights in the atmosphere, which are obtained from radiosondes.

This study contributes to two projects which aim for clarification of the relationship between the micro and macro properties of clouds and radiative transfer. These two projects are: the Tropospheric Energy Budget Experiment (TEBEX) and the Clouds and Radiation (CLARA) project. They are described concisely on the following pages.
1.1. TEBEX: Tropospheric Energy Budget Experiment

1.1.1. Introduction

The tropospheric energy budget is determined both by radiative transfer of energy and by transfer of energy and water due to air motions and precipitation. These transport processes are highly variable in time and space, mainly due to the presence of clouds, variability in landsurface properties and to small scale turbulence and convection.

For an adequate diagnosis of the tropospheric energy budget, data are needed both on the large scale flow properties and on small scale processes. Such data are scarce. Available global data sets suffer from a lack of detail, whereas experimental data with sufficient detail are generally only available for specific sites and short observational periods.

1.1.2. Observations

The observations of TEBEX started in the autumn of 1994 and were concluded on the last day of 1996. The experiment was conducted by KNMI in co-operation with the Royal Air Force, RIVM (National Institute of Public Health and the Environment), AUW (Agricultural University Wageningen) and UA (University of Amsterdam). The experiment was supported by the National Research Program for Global Air Pollution and Climate. In view of future operational applicability it was decided to primarily use commercially available instrumentation in TEBEX.

The TEBEX observations include:

- a Cloud Detection System (CDS), which is shown in figure 1.1.
- a main observing site at the Cabauw 200 metres mast experimental facility.
- a secondary observing site in a forest near Garderen equipped with a 36 metres mast.
- operational weather observations from synoptic stations on the TEBEX area.

1.1.3. Overview of TEBEX instrumentation

*Table 1.1 - Overview of TEBEX instrumentation*

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Location</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud lidar</td>
<td>CDS, Cabauw</td>
<td>wavelength 911 nm, max range 4 km, wavelength 911 nm, max range 7 km</td>
</tr>
<tr>
<td>IR-radiometer</td>
<td>CDS</td>
<td>spectral range 9.6 ... 11.5 μm</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>CDS</td>
<td>spectral range 0.3 ... 4 μm</td>
</tr>
<tr>
<td>Meteorological tower</td>
<td>Cabauw, Garderen</td>
<td>Vertical profiles of temperature, humidity, wind and visibility up to 200 m</td>
</tr>
<tr>
<td>Windprofiler/RASS</td>
<td>Cabauw</td>
<td>1290 Mhz profiler.</td>
</tr>
<tr>
<td>Sonic and IFM</td>
<td>Cabauw, Garderen</td>
<td>Measurement of turbulent fluxes of heat, water vapour, CO₂ and momentum.</td>
</tr>
<tr>
<td>Shortwave and longwave radiometers</td>
<td>Cabauw, Garderen</td>
<td>Measurement of the components of the radiation budget (shortwave and longwave) and net radiation</td>
</tr>
<tr>
<td>Heat flux plates</td>
<td>Cabauw</td>
<td>measurement of the soil heat flux.</td>
</tr>
<tr>
<td>Pressure sensors</td>
<td>Cabauw</td>
<td>measurement of the water table depth.</td>
</tr>
<tr>
<td>Thermometer needles</td>
<td>Cabauw</td>
<td>measurement of the soil temperatures at different depths.</td>
</tr>
<tr>
<td>NOAA/AVHRR</td>
<td>space</td>
<td>5 spectral channels; 2-4 times a day.</td>
</tr>
<tr>
<td>Meteosat</td>
<td>space</td>
<td>3 spectral channels; every half hour.</td>
</tr>
</tbody>
</table>
Figure 1.1. Cloud Detection System
1.2. **CLARA : Clouds and Radiation**

1.2.1. **Introduction**

The CLARA-project focuses on microphysics, its relation with the macro properties of clouds and its importance for routine observations of clouds by satellite and groundbased remote sensing. The information from the field campaigns are used to improve routine retrieval methods and to test detailed models for clouds and radiative transfer. These case studies will further serve as a testbed for parameterizations, that will be included in general circulation models.

Advanced groundbased remote sensing techniques like radar and lidar, as well as satellites play a crucial role in the monitoring of clouds. The algorithms which are used to derive physical parameters from these measurements are based on several crude assumptions about the micro-physical properties of the cloud and the relation between these properties and the measured (macro-physical) properties. This project offers the opportunity for validation of the different remote sensing techniques with in situ measurements.

1.2.2. **Objectives**

- To produce a validated data set on clouds and cloud-radiation interaction. This campaign-data set is composed of many cloud parameters derived from the different instruments, specified in table 1.2.

<table>
<thead>
<tr>
<th>Cloud parameter</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base height</td>
<td>lidar ceilometers, atmospheric radar, RIVM-lidar</td>
</tr>
<tr>
<td>Top height</td>
<td>atmospheric radar, NOAA/AVHRR; For thin clouds the RIVM-lidar system and the lidar ceilometers are also able to observe the cloud top.</td>
</tr>
<tr>
<td>Base temperature</td>
<td>IR-radiometers</td>
</tr>
<tr>
<td>Top temperature</td>
<td>NOAA/AVHRR, Meteosat</td>
</tr>
<tr>
<td>Size distribution</td>
<td>lidar ceilometers, atmospheric radar, lidar, NOAA/AVHRR</td>
</tr>
<tr>
<td>Droplet size distribution</td>
<td>FSSP on aircraft and in cloud chamber</td>
</tr>
<tr>
<td>Vertical velocity in the clouds</td>
<td>atmospheric radar</td>
</tr>
<tr>
<td>Optical depth</td>
<td>RIVM-lidar, NOAA/AVHRR, lidar ceilometers</td>
</tr>
<tr>
<td>Liquid water content</td>
<td>FSSP on aircraft, microwave radiometer, atmospheric radar, NOAA/AVHRR</td>
</tr>
</tbody>
</table>

- To validate and calibrate the retrieval algorithms of various groundbased and satellite remote sensing instruments. This will improve the quality of the KNMI Cloud Detection System.

- To validate cloud- and radiative transfer models and parameterizations of clouds and radiation which are developed at KNMI.
1.2.3. CLARA instruments used in this study

Two satellite based instruments and one groundbased instrument were used in this study, which are

- **AVHRR** (*Advanced Very High Resolution Radiometer*) aboard
  *NOAA* (*National Oceanic and Atmospheric Administration*)
  *POES* (*Polar Orbiting Environmental Satellite*)

<table>
<thead>
<tr>
<th>Sensor height</th>
<th>833 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal resolution</td>
<td>6 hours</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>1.1 × 1.1 km subsatellite</td>
</tr>
<tr>
<td>Channel 1</td>
<td>0.58 ... 0.68 μm</td>
</tr>
<tr>
<td>Channel 2</td>
<td>0.73 ... 1.1 μm</td>
</tr>
<tr>
<td>Channel 3</td>
<td>3.6 ... 3.9 μm</td>
</tr>
<tr>
<td>Channel 4</td>
<td>10.3 ... 11.3 μm</td>
</tr>
<tr>
<td>Channel 5</td>
<td>11.5 ... 12.5 μm</td>
</tr>
</tbody>
</table>

- **METEOSAT**

<table>
<thead>
<tr>
<th>Sensor height</th>
<th>35.800 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal resolution</td>
<td>30 minutes</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>5 × 9 km subsatellite</td>
</tr>
<tr>
<td>Channel 1</td>
<td>0.5 ... 0.9 μm</td>
</tr>
<tr>
<td>Channel 2</td>
<td>5.7 ... 7.1 μm</td>
</tr>
<tr>
<td>Channel 3</td>
<td>10.5 ... 12.5 μm</td>
</tr>
</tbody>
</table>

- **Heimann infrared radiometer (groundbased)**

<table>
<thead>
<tr>
<th>Sensor height</th>
<th>95 metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal resolution</td>
<td>10 seconds</td>
</tr>
<tr>
<td>Channel</td>
<td>9.6 ... 11.5 μm</td>
</tr>
</tbody>
</table>

The spectral response functions of these instruments, as used in this study, can be seen in figure 2.3., page 12.
2. Background

2.1. Atmospheric Radiation

The main components of the atmosphere are O₂ and N₂, which take in over 99% of the total volume of the atmosphere. These gases mainly absorb at wavelengths in the ultra-violet (UV) region, except for the O₂-A and O₂-B intervals (around 760 and 690 nm, respectively). Changes in the pressure and temperature profile of the atmosphere change the shape of the molecular absorption intervals. The temperature has an influence on the ‘strength’ of the absorption intervals due to population changes in the molecular energy levels. Pressure changes affect the width of the absorption intervals, because the decay time is dependent on pressure. Besides molecules, the atmosphere contains small particles like dust, water droplets, particles formed by photochemical reactions and particles originating from volcanic explosions.

Blackbodies

A so-called blackbody absorbs all incoming energy; and it radiates the same amount of energy.

The total amount of emitted radiation per square meter of a blackbody can be described by the Stefan-Boltzmann law:

\[ E_b = \sigma \cdot T^4 \]  

\( E_b \) = emitted radiation \hspace{1cm} [W m\(^2\)]
\( \sigma \) = emission coefficient \hspace{1cm} [5.67 \times 10^{-8} W m^{-2} K^{-4}]
\( T \) = temperature \hspace{1cm} [K]

The amount of energy that is radiated by a blackbody at wavelength \( \lambda \) is given by Planck’s law:

\[ E_{\lambda b} = \frac{2 \pi h c^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{\kappa \lambda T}} - 1} \]  

\( E_{\lambda b} \) = radiated energy \hspace{1cm} [W m\(^2\) m\(^{-1}\)]
\( h \) = Planck constant \hspace{1cm} [6.63 \times 10^{-34} Js]
\( c \) = speed of light \hspace{1cm} [3 \times 10^8 m s\(^{-1}\)]
\( \lambda \) = wavelength \hspace{1cm} [m]
\( k \) = Boltzmann constant \hspace{1cm} [1.38 \times 10^{-23} J K\(^{-1}\)]
The spectrum of electromagnetic radiation is categorised according to wavelength as follows:

- 0.001 μm ... 0.4 μm : ultra-violet
- 0.4 μm ... 0.76 μm : visible light
- 0.76 μm ... 4 μm : near infrared
- 4 μm ... 25 μm : thermal infrared
- 25 μm ... 1000 μm : far infrared

It is important to note that 99% of the solar energy is located in the wavelength interval from 0.2 μm to 4 μm. This can also be seen from a different point of view. Because the surface temperature of the sun is about 6000 K, it can be seen as a blackbody at that temperature. The earth and clouds radiate at an average temperature of 288 K. Because of this large temperature difference the spectral emission of the sun and that of the earth and clouds can very well be measured separately, as shown in figure 2.1.

*Figure 2.1 - Peak-normalised spectral emission of blackbodies at 6000 and 288 K*
Absorption

Energy can be absorbed in different ways, e.g. by:

- increase of rotational energy of a molecule \((\lambda = 0.1 \ldots 10 \text{ mm})\)
- increase of vibrational energy of atoms along their connecting line \((\lambda = 1 \ldots 40 \text{ \mu m})\)
- changes in electron configuration \((\lambda \approx 0.1 \ldots 1 \text{ \mu m})\)

Absorption is determined by the use of an absorption coefficient. This absorption coefficient is defined as the fraction of incoming energy that is absorbed, and can thus be represented by the following equation:

\[
\alpha = \frac{E_{\text{abs}}}{E_{\text{in}}}
\]  

(2.3)

Because a blackbody absorbs all incoming energy its absorption coefficient \(\alpha = 1\).

The absorption of radiation in the atmosphere takes place as follows:

- ultra-violet (UV) ionisation/division of molecules and absorption by \(O_2\) and \(O_3\)
  - \(O_2, O_3\) \(\lambda < 0.24 \text{ \mu m}\)
  - \(O_1\) \(\lambda 0.24 \ldots 0.32 \text{ \mu m}\)

- infrared (IR) absorption by \(O_3, H_2O\) and \(CO_2\)
  - \(O_3\) strong narrow absorption interval at \(9.7 \text{ \mu m}\)
  - \(H_2O\) \(\lambda < 4 \text{ \mu m}\)
  - \(\lambda 5 \ldots 8 \text{ \mu m}\)
  - \(\lambda > 11 \text{ \mu m}\) (rapidly increasing)
  - \(CO_2\) \(\lambda 13 \ldots 17 \text{ \mu m}\)

This means, that almost all of the longwave radiation is absorbed by the atmosphere, except for the radiation in the interval from 8 to 11 \(\mu m\); the so-called 'atmospheric window'.

The above mentioned absorption can be observed by comparing radiative calculations from Modtran 3 which simulate measurements at a cloud with and without an atmosphere. An example case of such calculations is shown below.

Example

In this example a blackbody of 17.3 °C at 0 m describes the cloud. This unrealistic cloud height is used in order to determine the influence of the entire atmosphere, and not just the part of the atmosphere that is situated between the cloud and the sensor.

The results from simulated satellite based measurements with and without September 1st 1996 15:00 atmosphere are shown in figure 2.2.
Figure 2.2 - Radiance calculations (satellite based) with and without September 1st, 1996, 15:00 atmosphere, performed by Modtran 3

The O₃ absorption peak at 9.7 µm is prominently visible in figure 2.2, as well as the absorption intervals from CO₂ and H₂O, at 13 to 17 µm and 5 to 8 µm, respectively.

Figure 2.3 - Spectral response functions used in this study

Figure 2.3 in combination with figure 2.2 shows that the largest influence of the absorption on measurements from the Heimann IR radiometer is caused by the O₃ absorption peak. The AVHRR channel 5 spectral response function has its peak at about 12.2 µm, and therefore the absorption by water is most likely to influence these measurements. Measurements from Meteosat and AVHRR channel 4 are influenced the least.
2.2.  \textit{Modtran 3}

2.2.1. Introduction

The Modtran code has been developed by the US Air Force Geophysics Laboratory (AFGL) starting in 1972. It has been written in the FORTRAN style of the seventies.

The version used in this study is Modtran 3 v 1.5.

2.2.2. Specifications

Modtran 3 calculates:

- atmospheric transmittance
- atmospheric background radiance
- single scattered solar and lunar radiance
- multiple scattered solar and thermal radiance
- direct solar irradiance

Modtran includes molecular absorption as well as scattering. It operates at moderately high spectral resolution (1 cm$^{-1}$ = 1 wave per cm) in the range of 0 to 50,000 cm$^{-1}$ in steps of 1 cm$^{-1}$ (0.2 μm to infinity).

The code consists of several default profiles that determine the spectral behaviour of molecular species (0 ... 100 km), like absorption and refraction.
Also, several representative atmospheric, aerosol, cloud and rain models are incorporated in the code. A climatology can be chosen by selecting one out of six reference atmospheres, which all define density and mixing ratios of H$_2$O, O$_3$, CH$_4$, CO and NO$_2$, as well as temperature and pressure as a function of height.
All three of these properties can also be specified by the user.

The AFGL radiative transfer code, while perhaps conceptually and scientifically elegant, is not user-friendly, modular, or an example of state-of-the-art programming; mainly due to the open evolution. There is also a lack of documentation; both within the source code and in its backup reports.
3. Realisation

3.1. Operation of Modtran 3

The interface to the radiative transport model Modtran 3 is specified by non-interactive input and output, which is discussed below.

3.1.1. Input

The file that is required to specify calculation parameters like wavelength interval, viewing angle and the atmospheric parametrisation is called tape5, pointing out the similarity with the computer tape used to enter data in the early days of computing.

An example of such a file is given below.

<table>
<thead>
<tr>
<th>t</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>2</th>
<th>2</th>
<th>2</th>
<th>2</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>286</th>
<th>800</th>
<th>0.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>355.000</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>10 Jun 1996--</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0.004</td>
<td>1.021E+03</td>
<td>2.868E+02</td>
<td>9.500E+01</td>
<td>3.700E-01</td>
<td>2.300E-03</td>
<td>AAH222222222222</td>
<td></td>
<td></td>
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<td></td>
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<td>0.076</td>
<td>1.013E+03</td>
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<td>8.300E+01</td>
<td>3.700E-01</td>
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<td>AAH222222222222</td>
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<td>0.144</td>
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<td>2.878E+02</td>
<td>7.900E+01</td>
<td>3.700E-01</td>
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</tr>
<tr>
<td>0.210</td>
<td>9.968E+02</td>
<td>2.888E+02</td>
<td>7.500E+01</td>
<td>3.700E-01</td>
<td>2.300E-03</td>
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<td>2.886E+02</td>
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<td>3.700E-01</td>
<td>2.300E-03</td>
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<tr>
<td>0.335</td>
<td>9.823E+02</td>
<td>2.885E+02</td>
<td>7.200E+01</td>
<td>3.700E-01</td>
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<td>3.700E-01</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(radiosonde profile partly skipped)

6.252 4.699E+02 2.555E+02 3.100E+01 3.700E-01 2.300E-03 | AAH222222222222 |
7.493 3.970E+02 2.461E+02 3.800E+01 3.700E-01 2.300E-03 | AAH222222222222 |
8.938 3.234E+02 2.339E+02 2.900E+01 3.700E-01 2.300E-03 | AAH222222222222 |
10.688 2.486E+02 2.204E+02 2.200E+01 3.700E-01 2.300E-03 | AAH222222222222 |
12.779 1.786E+02 2.154E+02 7.000E+00 3.700E-01 2.300E-03 | AAH222222222222 |
15.236 1.212E+02 2.161E+02 1.000E+00 3.700E-01 2.300E-03 | AAH222222222222 |
18.134 7.580E+01 2.166E+02 1.000E+00 3.700E-01 2.300E-03 | AAH222222222222 |
30.000 222222222222 |
35.000 222222222222 |
40.000 222222222222 |
45.000 222222222222 |
50.000 222222222222 |
50.000 0.004 180.000 .000 .000 .000 0 |
769 990 1 2 |

Figure 3.1 - Example of tape5 for Meteosat temperature correction (6:00 - June 10th, 1996)

This tape5, that is used for the purpose of temperature corrections, can roughly be divided into three parts, hereafter called the front, profile and back, respectively.

Each part consists of one or more so-called cards, whose arrangement is shown in Appendix A.
The front part of tape5

The front, made up by the first four lines in figure 3.1, consists of card1, card1a, card2 and card2c, which, among other things, take care of the following:

- **card1** tells Modtran 3 to read in a new model atmosphere, that the output should be 'short' and that the boundary temperature is 286.8 K.
- **card1a** sets the CO₂ mixing ratio to a value of 355 ppmv (1995 value).
- **card2** turns off the aerosol attenuation in the calculation.
- **card2c** sets the number of atmospheric levels that have to be read in to 61, and defines the format of these lines to be the strict Lowtran format.

The profile part of tape5

The profile part consists of data obtained from radiosonde measurements. Modtran allows the user to specify a maximum of 61 lines, that should describe the entire atmosphere. Because a file containing radiosonde data consists of more than 61 lines, an appropriate selection of lines needs to be made. To obtain the most reliable atmospheric parameterization, one should use a large line density at the bottom of the atmosphere, because it has the largest influence on radiative measurements. This large influence is caused by the relatively large amount of particles in the lower atmosphere (relatively high pressure and humidity in comparison to the top of the atmosphere, visualized in figure 3.2)

![Graph]: The graph shows the pressure, humidity and temperature profile obtained from radiosonde measurements at 6:00 - June 10th, 1996 Atmosphere.

*Figure 3.2 - Pressure, humidity and temperature profile obtained from radiosonde measurements (6:00 - June 10th, 1996 Atmosphere)*
It was chosen to spread the profile lines logarithmically throughout the atmosphere. This has been found to give the best estimate of the radiative properties of the atmosphere. The profiles used to specify the June 10th, 6:00 atmosphere in Modtran 3 are depicted in figure 3.3.\(^1\)

\textbf{Figure 3.3 - Logarithmically spread profile points describing the atmosphere in Modtran 3}

In order to spread the profile lines logarithmically throughout the atmosphere, the lines near the earth surface should be very close to each other. However, the radiosonde measurements do not provide enough measurements near the earth surface to make the spread entirely logarithmical. It was chosen to select the next point from the radiosonde measurements, when no measurement near the logarithmical height value was available.

Therefore, the first part of these profiles (i.e. the nearest to the earth surface) is described by subsequent points from the radiosonde file, so in fact no logarithmical spread has taken place in this part. In the part where the logarithmical spread is taking place, it was chosen to average the values for the relative humidity and the temperature, to provide an accurate description of the atmosphere.

\(^1\) Note that instead of the absolute humidity, the relative humidity is shown. This was chosen because the relative humidity can be obtained directly from radiosonde measurements and is used as is in the further course of this report.
The back part of tape5

The back part of tape5 consists of card3, card4 and card5.

card3 determines the geometrical path along which the calculation has to be made; in this case from 50 km to 4 m.
card4 defines the spectral range of the calculation; in this case from 769 to 990 cm\(^{-1}\), in steps of 1 cm\(^{-1}\).
card5 tells Modtran 3 to stop.

3.1.2. Output

After performing the requested calculations, Modtran 3 writes the output to three output files, called tape6, tape7 and tape8.

tape6 contains the complete output of the Modtran 3 model, as well as the input as it was interpreted by the code, which can be useful for tracing errors.
tape7 consists of a header followed by the spectral data. This spectral data can be used for further processing of the results.
tape8 can contain three kinds of spectral data, dependent on the type of calculation that is performed.
3.2. **Program description**

3.2.1. **Introduction**

The program *create* and its subprograms were written in ANSI-C release 5.3 on a Silicon Graphics INDY workstation running UNIX operating system. It provides an interface for Modtran 3, that simplifies the use of this radiative transfer model for cloud temperature corrections on groundbased and satellite based measurements. It also makes automation of these corrections possible, which is useful for processing large amounts of data.

A program flow diagram from the main program *create* is shown on pages 19 to 21.

3.2.2. **Description**

A description of the activities of the modules which are depicted in the program flow diagram is shown below. For a more detailed description see Appendix B.

- *create*: creates the Modtran 3 input file, and uses Modtran 3 to calculate the temperature corrections while iterating through the specified atmosphere.
- *check_file*: checks important files for existence and integrity.
- *build_fran*: builds the front of tape5.
- *build_prof*: builds the profile part of tape5.
- *build_back*: builds the back part of tape5.
- *set_date*: sets several date dependent parameters in tape5.
- *set_height*: sets height from the beginning or the end of the Modtran 3 calculation.
- *progress*: shows the progress of create.
- *filter*: applies a filter to the output spectral radiances in tape6, thus obtaining the integrated radiance.
- *analyse*: analyses the create output file mod-file to obtain a temperature correction table.
3.2.3. Program flow diagram

(Figure 3.4)
Type of instrument

- downloading
- uplooking

1. Execute `set_height`

2. $i = PRF_LINES$

3. Execute `set_height`

4. Execute `progress`

5. Execute `filter` (filterfile)

6. $i > = 2$? (YES/NO)

7. $i <= PRF_LINES$? (YES/NO)

8. $i = 1$

9. Execute `set_height`

10. Execute `progress`

11. $i ++$

12. Execute `filter` (filterfile)
3.2.4. Output

The output of the main program 'create' consists of two files whose filenames are the same as the radiosonde file name, except for the extensions. The extensions of the output files are ".mod" and ".ana". The first extension indicates that the file results from a Modtran 3 calculation, while the second indicates that we are dealing with the results of an analysis. This last file is printed to the screen at the end of the program, as indicated in the flow diagram above.

The first file, further indicated as the mod-file, consists of a table containing radiosonde parameters and the filtered radiance.

An example of a part of such a file is shown below in table 3.1.

<table>
<thead>
<tr>
<th>z [km]</th>
<th>p [mbar]</th>
<th>T_{radiosonde} [K]</th>
<th>RH [%]</th>
<th>R_{filtered} [W m^{-2} sr^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.004</td>
<td>1021</td>
<td>286.9</td>
<td>95</td>
<td>10.042</td>
</tr>
<tr>
<td>0.076</td>
<td>1013</td>
<td>286.6</td>
<td>83</td>
<td>10.007</td>
</tr>
<tr>
<td>0.144</td>
<td>1005</td>
<td>287.8</td>
<td>79</td>
<td>10.150</td>
</tr>
<tr>
<td>0.210</td>
<td>996.8</td>
<td>288.8</td>
<td>75</td>
<td>10.273</td>
</tr>
<tr>
<td>0.275</td>
<td>989.3</td>
<td>288.7</td>
<td>73</td>
<td>10.261</td>
</tr>
<tr>
<td>0.335</td>
<td>982.3</td>
<td>288.5</td>
<td>72</td>
<td>10.232</td>
</tr>
<tr>
<td>0.395</td>
<td>975.4</td>
<td>288.2</td>
<td>70</td>
<td>10.196</td>
</tr>
</tbody>
</table>

(file partly skipped)

6.252 | 469.9 | 255.6 | 31 | 5.942 |
7.493 | 397.0 | 246.2 | 38 | 4.921 |
8.938 | 323.4 | 234.0 | 29 | 3.767 |
10.688 | 248.6 | 220.4 | 22 | 2.702 |
12.779 | 178.6 | 215.4 | 7 | 2.367 |
15.236 | 121.2 | 216.1 | 1 | 2.412 |
18.194 | 75.8  | 216.7 | 1 | 2.451 |

*Table 3.1 - Example of the structure of the mod-file from Meteosat, 6:00, June 10th 1996*
The file with the ".ana" extension, further indicated as the ana-file, contains the same values as the mod-file. Besides that, it contains an extra column, in which the temperatures corresponding to the filtered radiances are shown. This temperature is the temperature that the instrument will measure if there is a cloud boundary at the height specified in the first column.

An example of a part of an ana-file is shown below in table 3.2.

<table>
<thead>
<tr>
<th>z[km]</th>
<th>p[mbar]</th>
<th>RH[%]</th>
<th>$T_{corrected}$ [°C]</th>
<th>$T_{measured}$ [°C]</th>
<th>$R_{filtered}$ [W m$^{-2}$ sr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.004</td>
<td>1021</td>
<td>95</td>
<td>13.7</td>
<td>12.3</td>
<td>10.042</td>
</tr>
<tr>
<td>0.076</td>
<td>1013</td>
<td>83</td>
<td>13.4</td>
<td>12.1</td>
<td>10.007</td>
</tr>
<tr>
<td>0.144</td>
<td>1005</td>
<td>79</td>
<td>14.6</td>
<td>13.0</td>
<td>10.150</td>
</tr>
<tr>
<td>0.210</td>
<td>996.8</td>
<td>75</td>
<td>15.6</td>
<td>13.8</td>
<td>10.273</td>
</tr>
<tr>
<td>0.275</td>
<td>989.3</td>
<td>73</td>
<td>15.5</td>
<td>13.7</td>
<td>10.261</td>
</tr>
<tr>
<td>0.335</td>
<td>982.3</td>
<td>72</td>
<td>15.3</td>
<td>13.5</td>
<td>10.232</td>
</tr>
<tr>
<td>0.395</td>
<td>975.4</td>
<td>70</td>
<td>15.0</td>
<td>13.3</td>
<td>10.196</td>
</tr>
</tbody>
</table>

(file partly skipped)

| 6.252 | 469.9   | 31    | -17.6                | -17.7               | 5.942                            |
| 7.493 | 397.0   | 38    | -27.0                | -27.1               | 4.921                            |
| 8.938 | 323.4   | 29    | -39.2                | -39.2               | 3.767                            |
| 10.688| 248.6   | 22    | -52.8                | -52.8               | 2.702                            |
| 12.779| 178.6   | 7     | -57.8                | -57.8               | 2.367                            |
| 15.236| 121.2   | 1     | -57.1                | -57.1               | 2.412                            |
| 18.194| 75.8    | 1     | -56.5                | -56.5               | 2.451                            |

*Table 3.2 - Example of the structure of the ana-file from Meteosat, 15:00, June 10th 1996*

$^2$ Note that $T_{radiosonde}$ from table 3.1 and $T_{corrected}$ from table 3.2 have the same values except for their units.
### 3.3. How to implement a new instrument

To implement a new instrument, the following steps need to be taken:

- creating the directories where the software should be located.
- compiling the source code, using a new initialisation file\(^3\).

In the initialisation file "ini.h", which is used while compiling, the user can specify several properties of the instrument and of the way the correction calculation will take place.

```c
#define INSTRUMENT "uplooking"
#define SENSOR_HEIGHT 95 /* in metres */
#define ZENITH_ANGLE 0 /* aberration from viewing line */

#define PRF_LINES 61 /* no. of lines from radiosonde profile */
#define STD_LINES 0 /* no. of lines from standard atmosphere */

#define MIN_WAVENR 870 /* in cm⁻¹ */
#define MAX_WAVENR 1042
#define STEP_WAVENR 1

#define FILTER "heim_ir_block.fil"
#define TEMP_VS_RAD "kt1585.tvr"

#define MOD_PATH "/sd3/your/destination/modtran3"
#define ORG_PATH "/sd3/your/destination/modtran3/heimann"
#define DAT_PATH "/sd3/your/destination/modtran3/heimann/radiosondes"
#define FIL_PATH "/sd3/your/destination/modtran3/heimann/Filters"
#define TVR_PATH "/sd3/your/destination/modtran3/heimann/T_vs_rad"
#define OUT_PATH "/sd3/your/destination/modtran3/heimann/Output"
```

---

**Figure 3.5 - Example initialisation file for Heimann IR radiometer**

The first parameters describe the instrument geometry.

- **INSTRUMENT**: type of instrument; uplooking or downlooking.
- **SENSOR_HEIGHT**: distance from the instrument to the surface of the earth in metres.
- **ZENITH_ANGLE**: angle between the viewing direction of the instrument and a vector perpendicular to the earth surface in degrees.

The next two parameters define how the atmospheric profile used in the calculations needs to be built.

- **PRF_LINES**: number of lines from the radiosonde file that have to be used as input for Modtran 3.
- **STD_LINES**: number of standard profile lines that have to be inserted after the lines from the radiosonde profile, to make sure that the entire atmosphere is defined from the object to the instrument (in case of satellite measurements).

---

\(^3\) It is important to enter the correct DESTINATION directory in `makefile` before compiling the source using the new `ini.h`.

\(^4\) `(PRF_LINES + STD_LINES)` cannot be bigger than 61 in the version of Modtran 3 (v 1.5) used in this study.
The following parameters are used to define the wavelength interval in which the amount of radiation has to be calculated.

\begin{itemize}
  \item \textit{MIN\_WAVENR} minimum wavenumber [cm\(^{-1}\)]
  \item \textit{MAX\_WAVENR} maximum wavenumber [cm\(^{-1}\)]
  \item \textit{STEP\_WAVENR} step size [cm\(^{-1}\)]
\end{itemize}

With the last part of the initialization file the important files and directories are defined.

\begin{itemize}
  \item \textit{FILTER} name of the filter file (file needs to be located in \textit{FIL\_PATH})
  \item \textit{TEMP\_VS\_RAD} name of the file containing the parameters for converting the filtered radiance to the measured temperature (file needs to be located in \textit{TVR\_PATH})
  \item \textit{MOD\_PATH} path of Modtran 3.
  \item \textit{ORG\_PATH} original path, indicating the location of `create' and its subprograms.
  \item \textit{DAT\_PATH} path in which the radiosonde files are located, sorted by day.
  \item \textit{FIL\_PATH} location of the filter files.
  \item \textit{TVR\_PATH} path in which the files containing temperature versus radiances are located.
  \item \textit{OUT\_PATH} path where output files (mod-file and ana-file) should be written to.
\end{itemize}

Usually, only the spectral response characteristics of the instrument are known. To obtain the temperature versus radiances table needed in the \textit{create} run an utility was written. This utility called \textit{bb\_rad} calculates the spectral blackbody radiance at several temperatures and applies the instrument response filter to these radiances, thus creating a temperature versus radiances table.
4. Results

4.1. Introduction

In order to test the temperature corrections, two testcases were analysed. The cloud covers for which the temperature corrections are performed had to be well defined, in order to avoid uncertainty in this part of the analysis. This meant looking for an optically thick stable cloud deck which is measured by various instruments to be able to intercompare the several outcomes. In practice this meant analysing data from the CLARA measurement campaigns, because many instruments were available during these campaigns.

The two test cases that were chosen are:

- April 19th, 1996, 6:00 UTC.
- September 1st, 1996, 14:45 to 15:15 UTC.

4.2. April 19th, 1996, 6:00 UTC

4.2.1. Introduction

This particular testcase is interesting for the CLARA project because of the stable cloud cover. The low altitude of this cloud cover made it suitable for aircraft measurements, thus producing in situ measurements of this water cloud.

The lidar (light detection and ranging) measurements are shown in figure 4.1.

\[ x(100 \text{ m km}) \]

\begin{align*}
0,20 - & 1,50 \\
1,50 - & 2,00 \\
2,00 - & 2,50 \\
2,50 - & 3,00 \\
3,00 - & 4,00 \\
4,00 - & 5,00
\end{align*}

*Figure 4.1 - Range corrected lidar return, KNMI-ESA lidar (Delft), April 19th, 1996*
From the lidar data the cloud base height and top height of the stationary cloud deck are determined.

Cloud base height \( 1500 \pm 100 \text{ m.} \)
Cloud top height \( 1700 \pm 100 \text{ m.} \)

4.2.2. Temperature corrections

Satellite based measurements

In figure 4.2 the different temperature profiles are plotted as they would be measured (if there were a cloud at that specific altitude) by the different satellite based instruments. The radiosonde temperature profile is also plotted. So, from figure 4.2 the correction for these satellite based measurements can be derived. The corrections are obtained using create (see section 3.2).

![Temperature correction plot for satellite based instruments](image)

*Figure 4.2 - Temperature correction plot for satellite based instruments;
Delft, April 19th, 1996, 6:00 UTC*
Discussion

In figure 4.3 an inversion layer can be seen at about 1700 metres. In an inversion layer the temperature increases with height. This hampers the rising of thermals, which can result in the formation of clouds at that altitude.

The largest temperature correction is calculated for the AVHRR channel 5. At an altitude of 1700 metres (cloud top in lidar analysis), the correction is 1.3 °C.

The corrections that are needed for the AVHRR channel 4 and Meteosat measurements are almost equal. The correction is 0.8 °C at 1700 metres for AVHRR channel 4, while the correction for Meteosat is slightly higher; 0.9 °C. The similarity in these corrections is caused by the small influence of absorption in both measurement channels (see also figure 2.2 and 2.3, page 12).
**Groundbased measurement**

The typical brightness temperature of the cloud base that was measured using the Heimann radiometer is about 2 °C for this particular testcase. The temperature correction that has to be performed on this measurement, can be derived from figure 4.4. The real cloud base temperature (= the radiosonde temperature) according to *create* is 1,5 °C at 1502 metres, which is also the cloud base height, as measured by the lidar.

![Diagram](image)

*Figure 4.4 - Heimann temperature correction; Delft, April 19th, 1996, 6:00*

**Discussion**

The lidar analysis and the corrected temperature plot both put the cloud base at an altitude of about 1500 metres, which is an indication that using this temperature correction plot helps enabling an intercomparison of the Heimann IR radiometer and the lidar system.

When no correction is made, one obtains a different cloud base altitude from the radiosonde measurements. In this particular case, looking up the uncorrected temperature of 2 °C in the radiosonde data would result in a cloud base altitude of 1383 m. This is a difference of more than 100 m.
4.3. *September 1st, 1996, 14:45 to 15:15 UTC*

4.3.1. Introduction

The interest in this particular testcase is mainly because of the CLARA project. There was convection in the cloud cover around 15:00 UTC which was well visible in radar measurements. This is the main reason why this day was picked as a collective study object for the contributing parties in CLARA. One of the analyses that has been made was a temperature histogram produced from cloudy pixels measurements using the AVHRR channel 4. The analysis is interesting for this study because it enables the verification of temperature corrections for this particular (and the other) satellite based instrument.

A lidar analysis of this testcase is depicted in figure 4.5.

![Figure 4.5 - Range corrected lidar return, KNMI-ESA lidar (Delft), September 1st, 1996](image-url)
Because the AVHRR channel 4 measurement closest to 15:00 is at 13:22 it was chosen to produce a temperature histogram of this measurement.

Figure 4.6 shows that a cloud cover temperature of 267.5 K (-5.7 °C) can be used when one wants to define the cloud top temperature.

![Figure 4.6 - Temperature histogram of AVHRR 4 measurements; TEBEX area; September 1st, 1996, 13:22 UTC](image)

Channel 1 of the AVHRR provides an overview of the cloud distribution, as can be seen in figure 4.7.

![Figure 4.7 - AVHRR channel 1 measurements over the Netherlands; 13:22 UTC](image)
4.3.2. Temperature corrections

The temperature correction on AVHRR channel 4 measurements was executed with two different atmospheres (at 12:00 and 15:00) because the AVHRR measurement is in between these radiosonde measurements describing the atmosphere.

The outcome of this analysis is shown in figure 4.8 and 4.9.

Figure 4.8 - AVHRR channel 4 temperature corrections; Delft, September 1st, 1996, 12:00 UTC

$T_{\text{meas}} =$ measured temperature

$T_{\text{corr}} =$ corrected temperature (= radiosonde temperature)

$dT =$ difference between $T_{\text{meas}}$ and $T_{\text{corr}}$
Figure 4.9 - AVHRR channel 4 temperature corrections; Delft, September 1st, 1996, 15:00 UTC

Discussion

The cloud top height derived from the lidar analysis in figure 4.5 is 8.6 kft, which is equal to 2.6 km. Correcting the cloud top temperature of -5.7 °C results in a temperature of -5.4 °C at 12:00 and in a temperature of -5.3 °C at 15:00. The corresponding cloud top heights are 3.2 and 3.4 km, respectively. The temperature corrections are small and the temperature does not vary strongly with height (about 1 °C between 2.6 and 3.2 km), so it is hard to make an accurate estimate of the cloud top height using this method.

The difference between the cloud top height obtained from the lidar analysis and the cloud top heights derived from the radiosonde profiles could also be due to the inability of the lidar system to penetrate optically dense clouds.

Furthermore, it could be caused by the fact that the radiosonde measurements in Delft do not represent the typical atmosphere of the whole TEBEX area.
4.4. Conclusions

The cloud base and top temperatures which are derived from radiation measurements can be corrected for the influence of the atmosphere using this interface for the radiative transport model Modtran 3.

Combining lidar measurements and temperature corrected Heimann measurements gives information on the optical properties of the cloud in the infrared.

Combining this with the cloud base and top temperatures yields a more accurate cloud description.
Acronyms and Symbols

AFGL : Air Force Geophysics Laboratory
ANSI : American National Standards Institute
AUW : Agricultural University Wageningen
AVHRR : Advanced Very High Resolution Radiometer
CDS : Cloud Detection System
CLARA : Clouds and Radiation
FSSP : Forward Scattering Spectrometer Probe
IFM : Infrared Fluctuation Meter
IR : Infrared
KNMI : Royal Netherlands Meteorological Institute
NOAA : National Oceanic and Atmospheric Administration
POES : Polar Orbiting Environmental Satellite
ppmv : Parts Per Million Volume
RASS : Radar Acoustic Sounding System
RH : Relative Humidity
RIVM : National Institute of Public Health and the Environment
TEBEX : Tropospheric Energy Budget Experiment
UA : University of Amsterdam
UTC : Universal Time Coordinated
UV : Ultra-violet

\( c \) : speed of light \([3.00 \times 10^8 \text{ m s}^{-1}]\)
\( E_b \) : emitted radiation per square metre of a blackbody \([\text{W m}^{-2}]\)
\( E_{\lambda b} \) : energy radiated by a blackbody at wavelength \( \lambda \) \([\text{W m}^{-2} \text{ m}^{-1}]\)
\( f \) : fraction \([\%]\)
\( h \) : Planck constant \([6.63 \times 10^{-34} \text{ J s}]\)
\( k \) : Boltzmann constant \([1.38 \times 10^{-23} \text{ J K}^{-1}]\)
\( p \) : pressure \([\text{mbar}]\)
\( R \) : radiance \([\text{W m}^{-2} \text{ sr}^{-1}]\)
\( r_n \) : normalised response
\( T \) : temperature \([\text{K} \text{ or } ^{\circ}\text{C}]\)
\( z \) : altitude \([\text{m} \text{ or } \text{km}]\)

\( \lambda \) : wavelength \([\text{m} \text{ or } \mu\text{m}]\)
\( \sigma \) : emission coefficient \([5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}]\)
References


Appendices

A - Structure of Modtran 3 Input

B - Program Description
Appendix A - Structure of Modtran 3 Input

**CARD1**  
Sets basic calculation parameters

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<thead>
<tr>
<th>MODTRN</th>
<th>Model choice</th>
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<tbody>
<tr>
<td>T</td>
<td>Modtran</td>
</tr>
<tr>
<td>F</td>
<td>Lowtran</td>
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<table>
<thead>
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<th>Selection of geographica/seasonal model atmosphere</th>
</tr>
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<tr>
<td>0</td>
<td>if meteorological data are specified (horizontal path only)</td>
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<td>1</td>
<td>Tropical</td>
</tr>
<tr>
<td>2</td>
<td>Midlatitude Summer</td>
</tr>
<tr>
<td>3</td>
<td>Midlatitude Winter</td>
</tr>
<tr>
<td>4</td>
<td>Subarctic Summer</td>
</tr>
<tr>
<td>5</td>
<td>Subarctic Winter</td>
</tr>
<tr>
<td>6</td>
<td>1976 US Standard</td>
</tr>
<tr>
<td>7</td>
<td>if a new model atmosphere has to be read in (radiosonde data)</td>
</tr>
</tbody>
</table>

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</tr>
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</tr>
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<td>Slant to space</td>
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<td>Transmittance mode</td>
</tr>
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<td>1</td>
<td>Thermal radiance mode</td>
</tr>
<tr>
<td>2</td>
<td>Radiance mode with single scattered solar/lunar radiance</td>
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<td>3</td>
<td>Calculation of direct solar/lunar irradiance</td>
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</tbody>
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<th>Atmospheric constituent specification</th>
</tr>
</thead>
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<td>T,P H2O O3 CH4 N2O CO</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Reset to default value = value from MODEL</td>
</tr>
<tr>
<td>1...6</td>
<td>Model number (see MODEL)</td>
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<tr>
<td>MDEF = 1</td>
<td>Use default profiles for CO2, O2, NO, SO2, NO2, NH3, HNO3</td>
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</table>

<table>
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<tr>
<th>IM</th>
<th>Atmospheric profile definition</th>
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<tbody>
<tr>
<td>0</td>
<td>Normal operation, MODEL data set (or rerun)</td>
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<tr>
<td>1</td>
<td>User input data (radiosonde data) (first run)</td>
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<th>NOPRT</th>
<th>Output files specification</th>
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<tr>
<td>-1</td>
<td>Normal tape6, tape7 and tape8</td>
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<tr>
<td>0</td>
<td>Normal tape6 and tape7</td>
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<tr>
<td>1</td>
<td>Normal tape7</td>
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<table>
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<tr>
<th>TBOUND</th>
<th>Boundary temperature [K] (if IEMSCT = 1, 2)</th>
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</table>

<table>
<thead>
<tr>
<th>SALB</th>
<th>Surface albedo (0.0 .. 1.0) of earth at average frequency of calculation</th>
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<tbody>
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<td>If left blank, blackbody is assumed</td>
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</table>
CARD 1A  Controls DISORT multiple scattering algorithm

LDISORT  (requires that IMULT = 1)
T = Activate DISORT multiple scattering algorithm
F = Continue with original Isaacs two-stream

ISTRM  Number of streams to be used by DISORT
2 = Better use Isaacs model
4 = 4 streams
8 = recommended at this time
16 = 16 streams

LSUN1  Solar irradiance specification
T = Read 1 cm⁻¹ solar irradiance from the file "sun2" (requires ISUN)
F = Use default solar irradiance as embedded in Modtran Block Data

ISUN  ISUN resolution scanning function (>3 cm⁻¹)
Values less than 5 cm⁻¹ are not recommended

CO2MIX  Replacement CO₂ mixing ratio (default = 330 ppmv)
1995 value = 335...360 ppmv

CARD 2  Aerosol/Cloud/Rain definition

IHAZE  Aerosol model for boundary layer (0-2 km)
0 = No aerosol attenuation included in the calculation
1 = Rural extinction, default VIS = 23 km
2 = Rural, VIS = 5 km
3 = Navy Maritime, sets own VIS
4 = Maritime, VIS = 23 km (Lowtran model)
5 = Urban, VIS = 5 km
6 = Tropospheric, VIS = 50 km
7 = User defined, reads CARD 2D, 2D1, 2D2
8 = Fog1 (Adveive fog), VIS = 0.2 km
9 = Fog2 (Radiative fog), VIS = 0.5 km
10 = Desert, sets own VIS from WSS

ISEASN  Seasonal tropo/stratospheral aerosol profile
0 = Season determined by value of MODEL
  Spring-Summer = 0, 1, 2, 4, 6, 7
  Fall-Winter = 3, 5
1 = Spring-Summer
2 = Fall-Winter
**IVULCN**
*Stratospherical aerosol profile, type of extinction*

0 = Background stratospheric profile and extinction
1 = Moderate volcanic profile, Aged volcanic extinction
2 = High volcanic, Fresh volcanic
3 = High volcanic, Aged volcanic extinction
4 = Moderate volcanic, Fresh volcanic
5 = Moderate volcanic, Background stratospheric
6 = High volcanic, Background stratospheric
7 = Extreme volcanic, Fresh volcanic

**ICSTL**
*Air mass character, only used when IHAZE = 3*
1...10 = Open ocean...Strong continental influence

**ICLD**
*Cloud and rain models*
0 = No clouds or rain
1 = Cumulus cloud, base 0.66 km, top 3.0 km
2 = Altostratus, 2.4-3.0
3 = Stratus, 0.33-1.0
4 = Stratus/Strato Cumulus, 0.66-2.0
5 = Nimbostratus, 0.16-0.66
6 = 2.0 mm/h at 0 km, 0.22 mm/h at 1.5 km
7 = 5.0, 0.2 at 2.0
8 = 12.5, 0.2 at 2.0
9 = 25.0, 0.2 at 3.0
10 = 75.0, 0.2 at 3.5
11 = User defined, reads cards 2D, 2D1, 2D2
18 = Standard Cirrus model
19 = Sub-visual Cirrus model
20 = NOAA Cirrus model (Lowtran6 model)

**IVSA**
*Army vertical structure algorithm for aerosols in boundary layer*
0 = No
1 = Yes

**VIS**
*Surface visual range [km], overriding default from IHAZE*
0 = Use default by IHAZE

**WSS**
*Wind speed [m/s], used when IHAZE = 3, 10*

**WHI**
*24 hour average wind speed [m/s], only used when IHAZE = 3*

**RAINRT**
*Rain rate [mm/hr]*

**GNDALT**
*Ground altitude above sea level [km]*
Modifiers aerosol profiles below 6 km altitude
CARD3  Geometrical path specification

H1  Initial altitude [km]
Observer altitude for IEMSCT = 1, 2

H2  Final altitude [km]

ANGLE  Initial zenith angle as measured from H1 [deg]
Observer zenith angle for IEMSCT = 1, 2

RANGE  Path length [km]

BETA  Earth centre angle subtended by H1 and H2 [deg]

RO  Radius of the earth [km]

LEN  Path length from H1 to H2
0 = Short path (default)
1 = long path through the tangent height

CARD3x  Geometrical path for direct irradiance (alternate to Card3 for IEMSCT = 3)

H1  Observer altitude [km]

H2  Tangent height of path to sun or moon [km]

ANGLE  Apparent solar/lunar zenith angle at H1 [deg]

IDAY  Day of the year

RO  Radius of the earth [km]

ISOURC  Extraterrestrial source
0 = Sun
1 = Moon

ANGLEM  Angle formed by sun, moon and earth [deg]
required if ISOURC = 1
CARD3A1  Optional card for solar/lunar irradiation ($IEMSCT = 2$)

**IPARM**  
*Solar/lunar geometry for CARD3A2*  
0 = Observer latitude/longitude, Source latitude/longitude  
1 = Observer latitude/longitude, Time  
2 = Azimuth, Zenith

**IPH**  
*Aerosol phase function*  
0 = Henyey-Greenstein (CARD3A2)  
1 = User defined (CARD3B)  
2 = MIE-generated (Lowtran)

**IDAY**  
*Day of the year (default = 93)*

**ISOURC**  
*Extraterrestrial source*  
0 = Sun  
1 = Moon

CARD3A2  Optional card for solar/lunar irradiation ($IEMSCT = 2$)

**PARM1**  
*Observer latitude [deg]*  
-90...90

**PARM2**  
*Observer longitude [deg]*  
0...360 = West of Greenwich

**PARM3**  
If IPARM = 0 : PARM3 = Source latitude [deg]  
If IPARM = 1,2 : PARM3 Not required

**PARM4**  
If IPARM = 0 : PARM4 = Source longitude [deg]  
If IPARM = 1,2 : PARM4 Not required

**TIME**  
*Greenwich time [decimal hrs]*

**PSIPO**  
*Path azimuth angle [deg], used when IPARM = 0, 1*

**ANGLEM**  
*Angle formed by sun, moon and earth [deg]*  
required if ISOURC = 1

**G**  
*Henyey-Greenstein asymmetry factor, used when IPH = 0*  
-1 = Complete backscattering  
0 = Isotropic/symmetric scattering  
1 = Complete forward scattering
CARD4  
*Spectral Range specification*

V1  
*Minimum wavenumber [cm⁻¹]*

V2  
*Maximum wavenumber [cm⁻¹]*

DV  
*Frequency increment [cm⁻¹], must be multiple of 5 for Lowtran*

FWHM  
*Full Width Half Maximum of triangular slit function*  
(used only in Modtran)

CARD2A  
*Optional card for cirrus (ICLD = 18, 19, 20)*

CTHIK  
*Cirrus thickness [km]*

0 = Use thickness statistics

>0 = User defined thickness

CALT  
*Cirrus base altitude [km]*

0 = Use calculated value

>0 = User defined value

CEXT  
*Extinction coefficient [km⁻¹] at 0.55 μm*

0 = Use 0.14 · CTHIK

>0 = User defined extinction coefficient

ISEED  
*Random number initializing flag*

0 = Use default mean values for cirrus

>0 = Initial value of seed for random number generator

CARD2BD  
*Optional card for Army VSA (IVSA = 1)*

ZCVSA  
*Cloud ceiling height [km], 0.0 for default*

ZTVSA  
*Cloud thickness [km], 0.0 for default*

ZINVSA  
*Height of the inversion or boundary layer [km], 0.0 for default*

CARD2C  
*Optional card for user profiles (MODEL = 0, 7)*

ML  
*Number of atmospheric levels (<62)*

IRD1  
*Read CARD2C2*

0 = No, 1 = Yes

IRD2  
*Read CARD2C3*

0 = No, 1 = Yes

TITLE  
*Title of new model atmosphere*

PROF_FORMAT  
*Format of CARD2C1...3*

0 = Strict Lowtran format

1 = Own format
Lowtran format:

\begin{align*}
0.000 & 9.800E+02 \ 2.830E+02 \ 2.415E+17 \ 3.500E+02 \ 1.024E+12 \ AABBBBBBBBBB \\
7.532E+12 & 3.773E+12 \ 4.136E+13 \ 2.095E-01 \ 0.000E+00 \ 3.438E+05 \ 8.968E+09 \\
0.000E+00 & 0.000E+00 \ 0.000E+00 \ 0.000E+00 \ 0.000E+00 \ 0.000E+00 \ 0.000E+00 \\
0.000E+00 & 0.000E+00 \ 0.000E+00 \ 0.000E+00 \ 0.000E+00 \ 0.000E+00 \ 0.000E+00 \\
6.768E+12 & 3.101E+12 \ 3.654E+13 \ 2.095E-01 \ 0.000E+00 \ 0.000E+00 \ 0.000E+00 \\
6.549E+12 & 7.900E+02 \ 2.740E+02 \ 1.202E+17 \ 3.500E+02 \ 1.133E+12 \ AABBBBBBBBBB \\
6.266E+12 & 2.789E+12 \ 3.415E+13 \ 2.095E-01 \ 0.000E+00 \ 4.084E+05 \ 4.004E+09 \\
0.000E+00 & 0.000E+00 \\
0.000E+00 & 0.000E+00 \\
\end{align*}

Own format:

First a list of the necessary quantities, then the format specification

HELP CARD2C1  Optional card for layer data and \( \text{H}_2\text{O}, \text{CO}_2, \text{O}_3 \) (MODEL=0, 7)

ZMLD  
Altitude of layer boundary [km]

JCHAR(1), P  
Unit ([mbar]=A, [atm]=B, [torr]=C, MODEL=1-6), Pressure

JCHAR(2), T  
Temperature unit ([K]=A, [°C]=B, MODEL=1-6), Temperature

JCHAR(3), WMOL(1)  
Unit, Value \( \text{H}_2\text{O} \)

JCHAR(4), WMOL(2)  
Unit, Value \( \text{CO}_2 \)

JCHAR(5), WMOL(3)  
Unit, Value \( \text{O}_3 \)

MODEL=1-6

JCHAR(J), J=6-14
Units for resp.: \( \text{N}_2\text{O}, \text{CO}, \text{CH}_4, \text{O}_2, \text{NO}, \text{SO}_2, \text{NO}_2, \text{NH}_3, \text{HNO}_3 \)

Units: vol. mix [ppmv] = A
        num. dens [cm^-3] = B
        mass mix [g/kg] = C
        mass dens [g/m^3] = D
        part.pressure [mbar] = E
        (H_2O) dew point [K] = F
        (H_2O) dew point [°C] = G
        (H_2O) rel.humidity [%] = H
        user defined = I

HELP CARD2C2  Optional card for additional molecular data (MODEL=0, 7)

WMOL(J), J=4-12  Values for resp.: \( \text{N}_2\text{O}, \text{CO}, \text{CH}_4, \text{O}_2, \text{NO}, \text{SO}_2, \text{NO}_2, \text{NH}_3, \text{HNO}_3 \)

HELP CARD2C3  Optional card for cloud/rain/aerosol (IRD2=1)

AHAZE, EQLWCZ  
Aerosol extinction at 0.55μm [km^-1], Equivalent liquid water content [g/m^3]

RRATZ  
Rain rate [mm/h]

IHA1, ICLD1, IVUL1  
Corresponds to IHAZE, ICLD, IVULCN (CARD2)
(Only one of these options is allowed)

ISEA1  
Corresponds to ISEASN (CARD2)
(Only one of these options is allowed)

ICHRI  
Aerosol region boundary: 0 = Same region, 1 = Boundary
CARD2C1  Optional card for layer data and H₂O, CO₂, O₃ (MODEL=0, 7)

| JCHAR(1-14) | ZMLD | T   | P | H₂O CO₂ | O₃ | RIVM O₃ profile |
|-------------|------|-----|---|---------|----|----------------|}
| AA66D6666666666 | .0 | 288.15 | .10133E+03 | 0 | 0 | .20000E-03 |
| AA66D6666666666 | 1.0 | 281.65 | .89814E+02 | 0 | 0 | .20000E-03 |
| AA66D6666666666 | 1.5 | 278.40 | .84470E+02 | 0 | 0 | .10330E-03 |
| AA66D6666666666 | 2.0 | 275.15 | .79386E+02 | 0 | 0 | .53400E-04 |
| AA66D6666666666 | 2.5 | 271.90 | .74555E+02 | 0 | 0 | .54400E-04 |
| AA66D6666666666 | 3.0 | 268.66 | .69965E+02 | 0 | 0 | .55400E-04 |
| AA66D6666666666 | 3.5 | 265.61 | .65068E+02 | 0 | 0 | .56300E-04 |
| AA66D6666666666 | 4.0 | 262.17 | .61475E+02 | 0 | 0 | .57200E-04 |
| AA66D6666666666 | 4.5 | 258.68 | .53842E+02 | 0 | 0 | .58900E-04 |
| AA66D6666666666 | 5.0 | 249.19 | .46999E+02 | 0 | 0 | .61600E-04 |
| AA66D6666666666 | 5.5 | 242.70 | .40880E+02 | 0 | 0 | .67000E-04 |
| AA66D6666666666 | 6.0 | 236.22 | .35425E+02 | 0 | 0 | .70500E-04 |
| AA66D6666666666 | 6.5 | 236.22 | .30640E+02 | 0 | 0 | .76800E-04 |
| AA66D6666666666 | 7.0 | 223.25 | .26393E+02 | 0 | 0 | .80400E-04 |
| AA66D6666666666 | 7.5 | 218.25 | .22599E+02 | 0 | 0 | .98200E-04 |
| AA66D6666666666 | 8.0 | 216.65 | .19306E+02 | 0 | 0 | .10700E-03 |
| AA66D6666666666 | 8.5 | 216.65 | .16484E+02 | 0 | 0 | .11300E-03 |
| AA66D6666666666 | 9.0 | 216.65 | .14075E+02 | 0 | 0 | .16100E-03 |
| AA66D6666666666 | 9.5 | 216.65 | .12018E+02 | 0 | 0 | .17000E-03 |
| AA66D6666666666 | 10.0 | 216.65 | .10263E+02 | 0 | 0 | .18800E-03 |
| AA66D6666666666 | 10.5 | 216.65 | .87644E+01 | 0 | 0 | .21600E-03 |
| AA66D6666666666 | 11.0 | 216.65 | .74850E+01 | 0 | 0 | .25000E-03 |
| AA66D6666666666 | 11.5 | 216.65 | .63927E+01 | 0 | 0 | .28600E-03 |
| AA66D6666666666 | 12.0 | 216.65 | .54601E+01 | 0 | 0 | .30400E-03 |
| AA66D6666666666 | 12.5 | 216.65 | .46638E+01 | 0 | 0 | .32100E-03 |
| AA66D6666666666 | 13.0 | 216.65 | .39031E+01 | 0 | 0 | .30400E-03 |
| AA66D6666666666 | 13.5 | 216.65 | .32072E+01 | 0 | 0 | .28600E-03 |
| AA66D6666666666 | 14.0 | 216.65 | .24881E+01 | 0 | 0 | .26800E-03 |
| AA66D6666666666 | 14.5 | 216.51 | .16129E+01 | 0 | 0 | .17900E-03 |
| AA66D6666666666 | 15.0 | 216.51 | .11576E+01 | 0 | 0 | .16200E-03 |
| AA66D6666666666 | 15.5 | 216.51 | .87863E+00 | 0 | 0 | .13600E-03 |
| AA66D6666666666 | 16.0 | 216.51 | .67756E+00 | 0 | 0 | .12000E-03 |

CARD2C2  Optional card for additional molecular data (MODEL=0, 7)

ZMLD, N₂O, CO, CH₄, O₂, NO, SO₂, NO₂, NH₃, HNO₃

CARD2C3  Optional card for cloud/rain/aerosol (IRD2=1)

ZMLD, AHAZE, EQLWCZ, RRATZ, IHA1, CLD1, IVUL1, ISEA1, ICHR1

CARD2D  Optional card for aerosols (IHAZE=7, ICLD=11 (CARD2))

IREG(1-4)
1 = Read aerosol data for altitude region
0 = Use default data for altitude region

CARD2D1  Optional card aerosol equiv. liquid water content

AWCCON  Conversion factor from elwc to extinction coeff. [kg.gm⁻³]

TITLE  Title for an aerosol or cloud region
CARD2D2  Optional card aerosol extinction (normalized at 0.55\(\mu\)m)

<table>
<thead>
<tr>
<th>VX</th>
<th>EXTC</th>
<th>ABSC</th>
<th>ASYM</th>
<th>Remarks</th>
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<th>Wavelength [(\mu)m]</th>
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<td>Extinction coefficient</td>
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<tr>
<td>ABSC</td>
<td>Absorption coefficient</td>
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<tr>
<td>ASYM</td>
<td>Asymmetry parameter</td>
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</table>

CARD3B1  Optional card for user-defined phase function (\(IPH=1\))

NANGLS  Number (< 50) of angles for user-defined phase functions

CARD3B2  Optional card for user-defined phase function (\(IPH=1\)) (1 to NANGLS)

| ANGLE | Scattering angle [decimal deg] |
| PHAR1 | User defined phase function at ANGLE, region 1 |
| PHAR2 | User defined phase function at ANGLE, region 2 |
| PHAR3 | User defined phase function at ANGLE, region 3 |
| PHAR4 | User defined phase function at ANGLE, region 4 |

CARD5  Recycle program

<table>
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<tr>
<th>IRPT</th>
<th>Card number from where to recycle the program</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Stop</td>
</tr>
<tr>
<td>1, 3, 4</td>
<td>Alternatives</td>
</tr>
</tbody>
</table>
Appendix B - Program Description

create
creates the Modtran 3 input file tape5.
performs iterations of radiative calculations through the atmosphere using Modtran 3.
saves the results.
prints results to screen.

calls:
check_file
build_frnt
build_prof
build_back
set_date
set_height
progress
filter
analyse

input:
yy = year
ddd = daynumber
hh = hour

output:
mod-file
ana-file (also printed to screen)

check_file
checks the integrity of the radiosonde file.
checks the existence of mod-file and ana-file.

input:
location and name of radiosonde file
location and name of mod-file
location and name of ana-file

build_frnt
builds the front of tape5

input:
the standard file front

output:
first part of tape5

build_prof
builds the profile part of tape5.

calls:
strip strips the header and footer from the radiosonde file
reduce reduces the number of lines from the radiosonde file to PRF_LINES
alter alters the lay-out

input:
radiosonde filename

output:
profile part of tape5

build_back
builds the back part of tape5

input:
the standard file back

output:
back part of tape5
**set_date** edits date dependent parameters in tape5 using the specified date.

**input:**
- yy
- ddd
- location of tape5

**set_height** sets one of the heights in tape5, using the linenumber from the profile. copies the characteristic values of the profile to mod-file if necessary.

**input:**
- position [min / max]
- line number
- location of tape5
- location and name of mod-file

**output:**
- first four columns of mod-file containing radiosonde parameters (line by line).

**progress** shows the progress

**input:**
- stepnumber
- total number of steps

**output:**
- progress indicator

**filter** filters spectral radiances from Modtran output file tape6 using a filterfile (.fil).
writes the integrated radiance to mod-file

**input:**
- location and name of filterfile
- location of tape6
- location and name of mod-file

**output:**
- column containing (filtered) integrated radiances in mod-file (line by line).

**analyse** analyses a mod-file, by looking up the temperatures corresponding to the (filtered) integrated radiances in a tvr-file (.tvr).

**input:**
- location and name of tvr-file
- location and name of mod-file

**output:**
- ana-file