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Chapter 1

Introduction

Motivation

Our climate is and will increasingly be influenced by anthropogenic interferences with the natural energy fluxes (Karl and Trenberth, 2003). There is a high probability that human-induced changes will take effect much faster than those caused by most natural processes; a lasting climate switch cannot be excluded (IPCC, 2001).

All predictions of future climate scenarios are afflicted with large uncertainties. For example, the projected warming over the next hundred years ranges from 1.4 K to 5.8 K (Wigley and Raper, 2001). About half of the uncertainty of this prediction is due to the lack of knowledge about future emissions; the given range was projected under the absence of changes in world economy and climate policy. The remaining uncertainty comes from problems with the climate models, especially from feedback processes such as the indirect aerosol effect, giving a global mean radiative forcing of the climate system for the year 2000, relative to 1750, in the range of 0 to -2 W m\(^{-2}\) (IPCC, 2001). This cooling effect is caused by the impact of aerosols on the radiative properties of clouds.

Clouds can presently be included by rough parameterizations only, causing serious uncertainties (Karl and Trenberth, 2003). The response of the climate to warming with respect to cloud cover and lifetime is not completely understood: It cannot even be predicted whether the amount of clouds will increase or decrease, partly because of the complexity of the water cycle. Yet an increase of high thin cirrus cloud cover may cause a stronger warming than a respective increase of CO\(_2\). This can be shown by comparing the climate forcing of clouds, aerosols, and gases using one-dimensional radiative transfer models. An increase of low cloud cover, in turn, can cause a more drastic negative climate forcing than the direct and the indirect aerosol effect. For illustration, Figure 1.1 shows the impact of a 50\% increase of key atmospheric parameters on the radiative forcing for a solar zenith angle of 55°. When adding thin cirrus clouds, a forcing up to 2 W m\(^{-2}\) is achieved. In contrast, thick cirrus clouds have a cooling effect. The individual contributions were calculated using the online-version of the Fu and Liou (1993) radiative transfer model.

When subdividing the current global mean energy budget into contributions from individual processes, absorption of shortwave radiation is one of the largest sources of uncertainty (Kiehl and Trenberth, 1997). The gap between calculations and measurements of shortwave absorption was mostly observed under cloudy conditions (Arking, 1996; Wendisch, 2003),
but also in the cloudless atmosphere polluted by aerosols (Halthore and Schwartz, 2000; Trentmann et al., 2003). Various reasons for this effect are being discussed in literature, such as horizontal cloud inhomogeneities (Valero et al., 2000; Scheirer and Macke, 2003) and water vapor absorption (Cess et al., 1996; Crisp, 1997).

The optical parameters of clouds are determined by their microphysical properties and by the extent and large scale geometry. Besides the cloud liquid water content, the drop size is an important quantity. The radiative effects of changes in this parameter have first been reported by Twomey (1977) who observed an increased cloud albedo for a decreased drop size if the liquid water content was held constant (so-called Twomey effect). With respect to cloud absorption, Wiscombe et al. (1984) and Knazykhin et al. (2002) showed that the presence of a few large cloud drops may alter cloud radiative properties drastically. Changes of the shape of the drop size distribution have also a strong impact on the formation of precipitation. In order to quantify these effects, accurate measurements of the drop size distribution are required. From this quantity, bulk microphysical parameters such as liquid water content, mean drop radius or drop concentration can be derived. For non-precipitating boundary layer clouds, the drop size distribution is usually measured with the Forward Scattering Spectrometer Probe (FSSP-100). This instrument has a number of shortcomings, part of which have been remedied in a follow-up version, the Fast-FSSP (Brenguière et al., 1998). One of the remaining problems of this probe is an artificial broadening of the size distribution. While condensational drop growth models predict a narrowing of the size distribution with height above cloud base, FSSP-100 and Fast-FSSP measurements show a broadening. This can only partly be explained by natural effects such as fluctuations of the vertical wind.
velocities and supersaturation (Cooper, 1989; Korolev, 1995) or turbulence (Pinsky and Khain, 2002). The remaining apparent broadening is caused by the instrument. Natural and instrumental contributions cannot be distinguished. This was one of the motivations for the development of the modified Fast-FSSP within this work. With this probe, the artificial broadening of the drop size distribution can be minimized (Schmidt et al., 2004).

Direct aircraft measurements characterize the state of the atmosphere only along the flight trajectory. In general, the spatial distribution and the time evolution of cloud fields cannot be determined from aircraft measurements alone. For long-term qualitative observations of cloud fields, indirect measurements using satellites or radars are more appropriate. From satellite radiance measurements, irradiances are retrieved to estimate the global energy budget, and the horizontal cloud structure is determined. High uncertainties are generated when deducing the cloud type or some vertical microphysical cloud properties from satellite measurements, especially when different cloud types overlap (Weare, 2000). Radars provide reflectivity profiles. The accuracy of the derived microphysical quantities is too low for using the measurements as input for radiative transfer modeling because assumptions and parameterizations are used for the retrieval. Therefore, in-situ measurements are needed for a quantitative characterization.

Cloud geometry and heterogeneities within the layer have as much impact on domain averaged cloud parameters (such as albedo and layer optical thickness) as the internal microphysical properties. A prominent candidate for the effects of inhomogeneities is the plane parallel albedo bias (e.g. Cahalan et al., 1994). The albedo of a cloud layer with horizontally varying optical thickness is systematically lower than for a horizontally homogeneous layer with the same average optical thickness. This (nonlinear) relationship causes errors in general circulation models, satellite retrievals, and weather models if subgrid cloud variability is not adequately considered. Furthermore, cloud inhomogeneities may enhance mean free photon pathlengths within clouds, which is currently discussed as one of the sources for the deviation between modeled and measured absorption (Marshak et al., 1998). Biases can be caused by the measurement strategy and by the radiative model calculations and are observed for various cloud types, e.g. for stratocumulus cloud fields (Titov, 1998) or deep convective clouds (Di Giuseppe and Tompkins, 2003). Both the albedo and absorption bias are affected by the aspect ratio of cloud fields or by the cloud layer dimensions in relation to the mean free photon path length.

Várnai and Davies (1999) classified the effects of cloud inhomogeneities with respect to cloud layer albedo and absorption. In the last decade, various studies have been performed about the effects of three-dimensional radiative transfer modeling under different cloud conditions, using both model clouds (Cahalan et al., 1994; Marshak et al., 1995; Scheirer and Macke, 2001, 2003) and measurements (Hignett and Taylor, 1996; Francis et al., 1997; Los and Duynkerke, 2000; for cirrus clouds: Buschmann et al., 2002). Parameterizations of the effects of subgrid cloud heterogeneities have been derived for special cloud scenarios (e.g. Los and Duynkerke, 2001). For constructing three-dimensional distributions of the liquid water content from aircraft measurements, assumptions were made for extending the one-dimensional measurements to three dimensions and thus for filling the gaps of missing information. For example, Los and Duynkerke (2000) assume a constant cloud top height. From in-cloud flight legs, the horizontal variation of cloud optical thickness is determined.
Differences are observed when using constant and variable cloud base height. Hignett and Taylor (1996) used the vertical velocity within a horizontal cloud leg to derive the geometrical thickness of cloud layers. Radiative transfer is very sensitive to the geometrical cloud top structure. The effects of geometrical cloud top variability and internal cloud heterogeneities are compared by Várnai and Davies (1999), showing that the geometrical variability may cause stronger effects than internal variability of cloud optical thickness as suggested by Los and Duynerkerke (2000). This is confirmed by Várnai (2000). Therefore, it is not justified to assume a constant cloud top height. So far, only a few studies reproduced cloud top height variability from aircraft measurements (e.g. Lenschow et al., 2000), and no radiative effects based on respective measurements were studied. Only little attention has been paid to the radiative impact of horizontal drop size variations, which were only implicitly accounted for in most studies through liquid water content variability. However, the effective radius is a further important input parameter for radiative transfer calculations. Presently, it can only be measured by the FSSP and its follow-up probes with sufficient accuracy. Räisänen et al. (2003) show that horizontal variations of the drop effective radius may partly counter-balance three-dimensional radiation effects. Therefore, the effective drop radius must explicitly be taken into account.

Outline

This work is a contribution to solving the above mentioned problems, arising when calculating the radiative properties of heterogeneous cloud fields. Instrumentation for accurate in-situ measurements of the cloud drop size distributions is introduced and methods are developed for characterizing the three-dimensional microphysical and macrophysical cloud structure if only airborne measurements are available, which is a rather common situation for field experiments. For one specific case, cloud fields are reproduced from the microphysical measurements, and three-dimensional radiative transfer calculations are performed. The model results are then compared with radiation measurements.

After introducing the terminology which is used in this work (chapter 2), an overview of instrumentation for airborne measurements of cloud microphysical and radiative properties is given (chapter 3). In this work, data from two instrument platforms, aircraft and tethered balloon, and from two major field experiments are used. The relevant information on these experiments is presented in chapter 4.

In chapter 5, the principle of operation and shortcomings of existing cloud drop sizing instruments are explained, and the new M-Fast-FSSP is introduced. It is shown how the systematic broadening of the measured drop size distribution can be minimized by decreasing the size of the sampling volume after the measurements. New accurate calibration schemes both for the drop size and for the size-dependent concentration measurement of the probe are introduced. Airborne and balloon-borne measurements are presented. For the balloon-borne application, a technique for deriving the drop speed from measurements of a specially recorded parameter is developed. The instrument is compared with existing cloud microphysical instrumentation.

In chapter 6, methods to derive three-dimensional cloud structure from airborne measurements are presented. This is required in situations where remote-sensing instrumentation is
not available. It is discussed under which circumstances aircraft measurements alone can be used to characterize the cloud field, and which parameters are appropriate in these cases. An overcast cloud case is analyzed, and three model clouds are reproduced using the statistical data from the measurements. Thereby, no unphysical assumptions are made about cloud structure, cloud top or base variability, or vertical profiles. The three model clouds are used as input for three-dimensional radiative transfer modeling (chapter 7). In chapter 8, the modeled irradiances and cloud layer properties for the three model clouds are compared with airborne and ground-based radiation measurements. To account for the variability throughout the measurements, probability density functions of the irradiance rather than mean values only are used.
Chapter 2

Terminology

In this chapter, the definitions of cloud microphysical properties (2.1) and radiative parameters (2.2) are introduced as far as they are required in the subsequent chapters. An overview of the instruments for measuring these parameters will be given in chapter 3.

2.1 Cloud Microphysical Properties

A cloud consists of water droplets and/or ice crystals, interstitial aerosol particles, and the atmospheric carrier gases. The water droplets are built from activated aerosol particles and may contain impurities. Large ice crystals and water drops can precipitate. Small liquid water droplets are spherical. Their size is characterized by the geometric diameter $D$. For non-precipitating boundary layer clouds, the droplet diameters typically range between 1 and 30 $\mu$m, and the concentration $N$ [cm$^{-3}$] is usually of the order of 100 to 1000 droplets per cm$^3$. This work is restricted to such clouds. Moreover, interstitial aerosol particles are not considered because their radiative impact is negligible here. Ice crystals and precipitation were not found for the presented measurement cases. Therefore, a spherical shape is assumed for the water droplets throughout this work.

Most microphysical parameters can be deduced from the drop number size distribution, $dN/dD$ [cm$^{-3}$ $\mu$m$^{-1}$], which specifies the drop number per cm$^3$ and per size bin $dD$ [$\mu$m]. The drop number concentration $N$ is obtained from $dN/dD$ by integrating over the whole range of $D$. The $a^{th}$ moment of the drop size distribution is given by

$$
\langle D^a \rangle = \frac{\int \frac{dN}{dD} D^a dD}{\int \frac{dN}{dD} dD} = \frac{1}{N} \int \frac{dN}{dD} D^a dD.
$$  

(2.1)

The effective radius of a cloud drop population $R_{eff}$ [$\mu$m] is defined as the ratio between third and second moment of the drop number size distribution:

$$
R_{eff} = \frac{1}{2} \frac{\langle D^3 \rangle}{\langle D^2 \rangle}.
$$  

(2.2)

The median volume diameter $MVD$ [$\mu$m] is the diameter which divides the drop mass distribution $dM/dD$ [g cm$^{-3}$ $\mu$m$^{-1}$] of a drop ensemble (total drop mass per cm$^3$ and size bin $dD$) into two parts with equal mass.

6
The drop surface area (particle surface area, \( PSA [\text{cm}^2 \text{ cm}^{-3}] \)) can be deduced from the drop surface distribution \( dS/dD [\text{cm}^2 \text{ cm}^{-3} \mu\text{m}^{-1}] \) or from the second moment of the number size distribution:

\[
PSA = \int \frac{dS}{dD} dD = \int \frac{dN \pi D^2}{dD} dD = \frac{\pi}{4} \langle D^2 \rangle N. \tag{2.3}
\]

The drop surface distribution and the \( PSA \) determine the radiative properties of the drop ensemble.

The liquid water content (\( LWC [\text{g m}^{-3}] \)) is the mass concentration of liquid water drops and is determined by integrating the drop mass distribution over the whole range of \( D \), or from the third moment of the number size distribution

\[
LWC = \int \frac{dM}{dD} dD = \int \rho \frac{dN \pi}{dD} D^3 dD = \rho \frac{\pi}{6} \langle D^3 \rangle N, \tag{2.4}
\]

where \( \rho [\text{g cm}^{-3}] \) is the water density. In the following, the term ‘size distribution’ will be used for the number size distribution \( dN/dD \), and ‘concentration’ for the number concentration \( N \).

The vertical gradient of the \( LWC \) within a cloud layer can be calculated from the assumption of adiabatically rising cloud parcels. The measured \( LWC \) is in general less or equal than the \( LWC \) obtained from the adiabatic model,

\[
LWC_{\text{ad}}(h) = C_w(h) h, \tag{2.5}
\]

where \( h \) is the height above cloud base. The moist adiabatic condensate coefficient \( C_w \) is constant with height above cloud base for thin (<1 km) stratuscumulus layers, and is a function of cloud base temperature and pressure (e.g. Brenguier, 1991).

The liquid water path (\( LWP [\text{g m}^{-2}] \)) is the column integrated liquid water content of a cloud layer of geometrical vertical thickness \( H \):

\[
LWP = \int_{z_b}^{z_b+H} LWC(z') dz' \tag{2.6}
\]

where \( z_b \) is the cloud base height. The adiabatic \( LWP \) can be derived from (2.5):

\[
LWP_{\text{ad}} = \frac{1}{2} C_w H^2. \tag{2.7}
\]

### 2.2 Solar Radiation

The power of solar radiation is given by \( \Phi [\text{W}] \), the radiant flux. The energy of the radiation is distributed over the wavelengths \( \lambda [\text{nm}] \) of the solar spectral range. Spectral quantities are denoted by a subscript \( \lambda \): \( d\Phi/d\lambda \equiv \Phi_{\lambda} [\text{W nm}^{-1}] \). Broadband quantities are obtained by integrating the spectral quantities over a wavelength interval. This work deals with spectral irradiances and layer properties. If not stated otherwise, the \( \lambda \)-subscripts and the term ‘spectral’ are omitted. The wavelength interval from 280 to 400 nm is called the ultraviolet (UV) band, the visible band (VIS) ranges from 400 to 770 nm, the short wavelengths of the infrared (IR) are called near infrared band (NIR, 770 to 1500 nm). Thermal radiation (4000 to 100000 nm), is emitted by the Earth and atmosphere and is not considered in this work.
The radiance \( L \) \([\text{W m}^{-2} \text{ sr}^{-1}]\) is the radiant flux per area \(dA\) and per solid angle \(d\Omega\):

\[
L = \frac{d^2 \Phi}{dA d\Omega}.
\]  

(2.8)

The irradiance \( F \) is mainly used for radiative budget calculations. It is defined as the radiant flux incident onto the horizontal area \(dA_\perp\) (see Figure 2.1):

\[
F = \frac{d\Phi}{dA} = \frac{d\Phi}{dA} \cos(\theta)
\]  

(2.9)

Figure 2.1: Geometry

where \(\theta\) is the incidence angle of the solar radiation. The downward irradiance \( F^\downarrow \) is obtained by integrating the radiance \( L \) over all directions coming from the upper hemisphere:

\[
F^\downarrow = \left. \frac{d\Phi}{dA_\perp} \right| = \int_{d\Omega^+} L(z, \theta_s, \theta', \varphi') \cos(\theta') \, d\Omega'.
\]  

(2.10)

The integration over the solid angles \( d\Omega' = d(\cos \theta') d\varphi' \) in the upper hemisphere is denoted by \( d\Omega^+ \) (\( \theta = 0^\circ \ldots 90^\circ, \varphi' = 0^\circ \ldots 360^\circ \)); \( z \) is the altitude, and \( \theta_s \) is the solar zenith angle (SZA), that is the angle of the sun with respect to zenith position. The azimuthal integration is denoted by \( \varphi' \). The definition for the upward irradiance is similar. It involves an integration of \( L \) over the lower hemisphere (\( \theta = 90^\circ \ldots 180^\circ, \varphi' = 0^\circ \ldots 360^\circ \)):

\[
F^\uparrow = \left. \frac{d\Phi}{dA_\perp} \right| = - \int_{d\Omega^-} L(z, \theta_s, \theta', \varphi') \cos(\theta') \, d\Omega'.
\]  

(2.11)

\( F^\downarrow \) and \( F^\uparrow \) are positive by definition because \( L > 0 \) and \( \cos(\theta) > (\angle)0 \) in the upper (lower) hemisphere. The net irradiance is defined as

\[
F_{net} = F^\downarrow - F^\uparrow = \int L(z, \theta_s, \theta', \varphi') \cos(\theta') \, d\Omega'.
\]  

(2.12)

with the integration over both hemispheres. If \( F_{net} > 0 \), there is an effective downward energy flux, and vice versa.

The actinic flux density \( E \) is derived from the radiance \( L \) by integrating over the upper and lower hemisphere without applying the cosine weighing:

\[
E = \int d\Omega L(z, \theta_s, \theta', \varphi') \, d\Omega'.
\]  

(2.13)

With this spectral isotropic quantity, the photolysis frequencies for specific gases can be calculated. This quantity will not be used in this work.

From the irradiance, the following layer properties are derived for a layer between altitudes \( z_b \) (base height) and \( z_t \) (top height): The absorbed irradiance \( F_a \) is the difference of the top and base net irradiances: \( F_a = F_{net,t} - F_{net,b} \). The layer absorptance \( A \), transmittance \( T \), and the reflectance \( R \) are defined by

\[
A = \frac{F_a}{F^\downarrow_t}
\]  

(2.14)

\[
T = \frac{F^\downarrow_b}{F^\downarrow_t}
\]  

(2.15)

\[
R = \frac{F^\uparrow_t - F^\uparrow_b}{F^\downarrow_t},
\]  

(2.16)
respectively, with \( A + T + R \equiv 1 \) by definition. The layer reflectance \( R \) quantifies the radiation reflected by the layer only, whereas the albedo

\[
a = \frac{F^\uparrow}{F^\downarrow}
\]

(2.17)

can be defined at any reference level, irrespective of the layer. The layer top albedo \( a_t = \frac{F_t^\uparrow}{F_t^\downarrow} \) contains reflections from the layer itself as well as from below. A special case is the surface albedo \( (z = 0) \). The layer properties can be calculated for a cloud or aerosol layer, and for the whole atmosphere with or without aerosols or clouds. The spectral layer properties are defined in the same way as in formulae (2.14) through (2.17), but using spectral irradiances. The wavelength dependence of the spectral surface albedo varies with the type of surface (e.g. land/sea).

The downward irradiance consists of two components: the part directly from the sun and the diffuse part from the scattered solar radiation. These components are treated separately by radiative transfer models. In the context of this work, the global irradiance, that is the sum of direct and diffuse irradiances is addressed.

The optical depth or thickness \( \tau \) (dimensionless) of a layer is given by

\[
\tau = \int_{z' = z_0}^{z_0 + H} \beta_{\text{ext}}(z') dz'
\]

(2.18)

where \( \beta_{\text{ext}} \, [\text{m}^{-1}] \) is the extinction coefficient. It is the sum of the absorption \( (\beta_{\text{abs}}) \) and the scattering coefficients \( (\beta_{\text{scat}}) \) and is composed of the individual contributions from the air, aerosol particles, and cloud drops. In presence of clouds, the predominant contribution to \( \beta_{\text{ext}} \) and \( \tau \) comes from the cloud drops. The ratio between scattering and extinction coefficient is the single scattering albedo: \( \omega_0 = \beta_{\text{scat}}/\beta_{\text{ext}} \). For water drops, \( \beta_{\text{ext}} \) and \( \omega_0 \) can be calculated from Mie theory which requires the drop number size distribution \( dN/dD \) and the refractive index \( \nu \) of water.

For (shortwave) solar radiation, the extinction coefficient \( \beta_{\text{ext}} \) can be estimated from the \( LWC \) and \( R_{\text{eff}} \) (Paltridge and Platt, 1976; Stephens, 1978):

\[
\beta_{\text{ext}} = \frac{3 \, LWC}{2\rho \, R_{\text{eff}}}
\]

(2.19)

For longwave radiation, this approximation cannot be used. For the optical thickness,

\[
\tau = \frac{3 \, LW \, P}{2\rho \, R_{\text{eff}}}
\]

(2.20)

follows from (2.18), (2.19) and (2.6).
Chapter 3

Instrumentation

3.1 Cloud Microphysical Properties

This section introduces some common instruments for in-situ measurements of cloud microphysical properties. Cloud structure can also be measured by remote-sensing instruments such as Radars, Lidars, infrared radiometers and acoustic sounding instruments (Sodar). Satellites are used for long-term global observations of cloud cover, type, optical thickness and other cloud parameters.

In-situ measurements are performed by aircraft or balloon platforms. They permit direct measurements of cloud parameters. However, they are only snapshots of a momentary state and cannot be used for long-term and spatially extended observations.

The dynamic range of microphysical parameters such as drop diameter or concentration is too large to be covered by a single instrument. Also, the parameters of interest vary considerably depending on the type of cloud. For warm, non-precipitating boundary layer clouds, the drop size distribution is sufficient to characterize the cloud microphysics. For other cloud types, phase information is required in addition. If ice crystals are present, their shape, size and the integral ice water content are adequate parameters for description. For mixed-phase clouds, both drop and crystal size distribution and the liquid and ice water content, along with shape information or orientation of the ice crystals may be necessary. Precipitation forms from large drops or ice crystals. Generally, these are not spherical.

The instruments for measuring size distributions are explained in 3.1.1. Bulk parameters such as $N$ or $LWC$ can either be deduced from the moments of the size distribution or measured by independent methods which are described in section 3.1.2.

3.1.1 Drop Size Resolving Instruments

An overview of drop size resolving instruments is given by Knollenberg (1981). They can be classified by the underlying physical process which is used for the size and concentration measurement: Imaging probes measure the shadow size of individual drops (Optical Array Probes) or store the interferogram of a drop population (holographic systems). Light scattering probes detect the forward scattering signal of single cloud drops (Forward Scattering Spectrometer Probe) or of drop populations (Cloud Drop Spectrometer). Other
instruments are based on physical sampling of the cloud constituents on some substrate (replicator probes) or on Doppler velocimetry.

Imaging Probes

Optical array probes (OAP), manufactured by Particle Measuring Systems, Inc. (PMS), Boulder, USA, were first described by Knollenberg (1970). The OAP-1D-P, shortly 1DP, and the OAP-1D-C (1DC) measure the size distribution of precipitation or cloud drops, respectively, by means of a one-dimensional photodiode-array. The drops are exposed to a laser beam and leave a shadow on the diode array. The number of shadowed elements is converted to drop size. The size resolution is determined by the magnification of the shadow size by the lens system and by the spacing of the individual photodiodes. The principle is only applicable in the regime of geometrical optics. For very small drops, refraction and diffraction prevents useable images on the diodes. The range of the 1DP is 300 to 4500 μm, the 1DC measures drops within 20 and 300 μm. The drop shape cannot be assessed. Therefore, the probes were extended to two-dimensional versions, the OAP-2D-P, (2DP, 200 - 6400 μm) and the OAP-2D-C, (2DC, 25 - 800 μm). These probes also consist of a one-dimensional photo-diode array, which in contrast to the 1D versions is read out periodically, providing data about the shape of the individual drops. Gayet et al. (1993) compared cloud measurements with these instruments. A modification of the OAP-2D-P is the OAP-2D-GA2, the so-called 2D-Greyprobe (Joe and List, 1987). In contrast to the 2DC-probe, it samples drop shadows with four different grey scales, permitting a better interpretation of the shadows on the limit of the applicability of geometrical optics. The lower size limit of the Greyprobe is therefore reduced to 10 μm.

In contrast to OAP probes, holographic systems can store the image of a drop ensemble. Lawson and Cormack (1995) present a digital holographic imaging system (DHIS) for aircraft use which takes laser snapshots of particles on a two-dimensional photodiode array. From these images, the individual particles can be reconstructed. The minimum detectable size for this probe is 5 μm, the maximum particle rate is 100 s⁻¹. Borrmann and Jaenicke (1993) describe a holographic system for the ground-based measurement of cloud drop size distribution as well as of the shape and velocity of the cloud constituents. Holographic methods are applied in favor of the PMS OAP probes if an exact knowledge of the crystal shape is desired. However, it is difficult and time-consuming to reconstruct the original particle shapes from the holograms. A limited automation of the data processing can be achieved by digital image analysis.

Light Scattering Probes

Below the threshold size for the applicability of geometrical optics, i.e., when the size of the object is of the same order or smaller than the wavelength of the light used by the instrument, diffraction prevents a geometrical detection. Optical scattering probes interpret the scattering signal of a drop or of a drop population. A straightforward implementation of this principle is the Forward Scattering Spectrometer Probe (FSSP-100), developed by PMS. A more detailed description of this instrument is given in chapter 5.1. Drops pass a laser beam, and their forward scattering signal (which is related to the drop size via Mie
theory) is used for counting them into a certain size class. The sample volume is set by an opto-electronic definition. The size range is about 2 to 50 μm. By two follow-up probes, problems of the FSSP-100 were partly remedied (Fast-FSSP: see 5.2, and M-Fast-FSSP: see 5.3). FSSP data can be viewed on-line during an experiment; data-processing, setup, and calibration are straightforward. However, there is a number of problems which can affect the measurements. Originally, the FSSP was designed for spherical water drops. However, Gayet et al. (1996) found that in mixed-phase and ice clouds, the measurement inaccuracy is small as long as the ice particles are spherical. Non-spherical ice crystals are mis-sized, and their concentration is overestimated (Gardiner and Hallet, 1985).

The cloud drop spectrometer (CDS) was first presented by Lawson and Cormack (1995). In contrast to the FSSP which sizes droplets one by one (‘single particle counter’), the CDS measures the forward scattered light of a drop population, thereby resolving the phase function of the drop ensemble with a fine angular resolution using a linear array of CCD photodetectors. The liquid water content can be determined directly by weighing the pixel measurement applying a method described in Blyth et al. (1984). The drop size distribution is retrieved by inverting the angular measurements which requires a post-experiment data-analysis. An application of the CDS during cloud measurements, and a comparison with data from other probes is discussed in Lawson and Blyth (1998).

Other Instruments

Replicator probes are based on a collection of cloud components on a substrate like a tape coated with oil. The rotating tape is first exposed to the cloud particles and subsequently dried. After evaporation, the particles leave a replica (copy) of themselves on the tape which is then photographed and analyzed by e.g. digital image processing. A state-of-the-art example of such a system, the Video Ice Particle Sampler (VIPS), and measurements in cirrus clouds are presented by Heymsfield and McFarquhar (1996). With this system, the shape of ice crystals can be determined for a size range within 5 and 300 μm. Above the upper diameter, fragmentation can occur. McFarquhar and Heymsfield (1996) characterize the instrument and compare measurements with other probes (e.g. with 2DP). Problems can occur with the collection efficiency causing uncertainties in the measured concentration. Furthermore, the probe can only be applied for low concentrations.

Laser Doppler velocimetry (LDV) is used for measurements of particle velocities. An extension of this principle is Phase Doppler particle analysis (PDPA, Bachalo, 1980). Two laser beams intersect and build the sample volume for a particle stream. When a drop passes the sample volume, the scattered light forms an interference fringe pattern. The particle’s movement causes a Doppler phase shift which is used for measuring the velocity, while the shape of the fringe pattern is detected to give the particle size. This method allows measurements even for high concentrations, giving the size distribution and the velocity distribution of the drop ensemble. Common PDPA cover a particle size range between 2 and 2000 μm, provided the particles are spherical. Measurements of PDPA and OAP probes in an icing channel are compared by Strapp et al. (2003).
3.1.2 Integrating Instruments

In cases where there is no need to know the size distribution in detail, the LWC or the ice water content can also be measured directly by integrating instruments.

The particle volume monitor (PVM-100, Gerber, 1991) is based on the same optical principle as the CDS described above. A cloud drop ensemble is exposed to a laser beam, and the forward scattering signal is weighed by means of two optical filters, providing a direct measurement of the LWC, and of the droplet surface area, respectively. The effective radius can be deduced from the ratio of these quantities. Gerber et al. (1994) present the airborne version PVM-100A. Wendisch et al. (2002b) performed wind tunnel tests (see also Strapp et al., 2003) and intercompared LWC measurements of the PVM-100A and FSSP probes, revealing a decreasing LWC sensitivity of the PVM-100A for drops with diameters above 20 \( \mu \text{m} \). For a \( \text{MVD} \) of 50 \( \mu \text{m} \), the efficiency of the PVM-100A drops to 50%.

Hotwire probes are based on the principle that the LWC can be calculated from measurements of the amount of heat released when vaporized. The King probe (manufactured by PMS, Boulder, USA) has a heated cylinder exposed to the airstream onto which droplets impinge. The temperature of the cylinder is kept constant by the probe, and the evaporation heat is thereby measured. The LWC can directly be deduced (King et al., 1978). The Nevzorov probe (Korolev et al., 1998) consists of two separate hotwire sensors for measuring the total and the liquid water content, respectively. Strapp et al. (2003) compared the measurements of various hotwire probes. They found differences between the instruments, especially with respect to the response to large drops and ice crystals. Critical for this kind of probes are the time constants of the electronics, collection efficiency, and convective heat-losses. The latter are automatically corrected by the Nevzorov probe. The collection efficiency and problems such as drop and crystal fragmentation depend on the individual geometrical setup and on drop size.

The counterflow virtual impactor (CVI) separates cloud droplets or crystals from the surrounding air and interstitial aerosol (Ogren et al., 1985) by applying a clean warm dry airflow towards flight direction through a porous tube around the sampling inlet. Ambient gases and particles with low inertia follow the stream lines around the CVI inlet tip. Only droplets larger than a cutoff aerodynamic diameter given by the flow conditions can enter the sampling inlet. The surrounding water and ice crystals are completely evaporated in the warm dry carrier gas, and the nonvolatile residual nuclei are left behind. The total water content of the sampled drops and crystals is deduced from humidity measurements (e.g. Lyman-alpha). A condensation particle counter (CPC) is used for determining the number of sampled residual nuclei, and a nephelometer can be used to measure their scattering coefficient. Twyoh et al. (2003) discuss measurements with a CVI system in the NASA icing tunnel and problems involved with collection efficiency especially for large drops.

In general, the integrating instruments supply more accurate LWC measurements compared to the values which are derived from drop size distribution measurements. For example, the systematic error of FSSP measured LWC is up to 50%, whereas an error of only 5% for the PVM measured LWC is indicated by the manufacturer.
3.2 Solar Irradiances

3.2.1 Solar-Broadband

Broadband instruments measure the total insolation and cover the whole solar spectrum. The wavelength range can be restricted to some selected bands such as IR or VIS by applying a set of optical filters. The sum of direct and diffuse global irradiance is measured by pyranometers. A description of this type of instruments and a discussion of error sources is given by Beaubien et al. (1998). A pyranometer consists of a plane optically black surface absorbing solar radiation. The surface heats up, and the temperature difference to the ambient air is measured by thermoelements. Widely used instruments are manufactured by Kipp & Zonen, Delft, Netherlands, and by Eppley Laboratory, Newport, USA (Precision Spectral Pyranometer, PSP). The wavelength range of these instruments is from about 300 to 3000 nm. The largest error source of either types are thermal offsets which are caused by changes of the ambient temperature. The cosine weighing is provided by the flat surface. The calibration is performed with standard lamps (Halthore and Schwartz, 2000).

In order to measure the diffuse irradiance, the pyranometers must be shaded from direct radiation. The direct irradiance can be measured with solar-tracking pyrheliometers, one of which is the Normal Incidence Pyrheliometer (NIP, Eppley Laboratory). This instrument tracks the direct sun. The measured radiation corresponds to normal incidence of the sun and must be weighed with $\cos(\theta_s)$ to account for the changing SZA.

Apart from problems with thermal offsets and other measurement uncertainties, another shortcoming of broadband instruments is that effects stemming from different wavelengths or bands cannot be distinguished. For example, the water vapor absorption bands represent an error source for measurements and modeling. For spectrally resolved measurements, in contrast, specific wavelengths can be chosen. In this work, only spectrally resolving instruments are used, which are introduced in the following section.

3.2.2 Spectral Albedometer

The spectral albedometer (Wendisch et al., 2001) was developed at IfT to overcome two problems of airborne irradiance measurements: missing spectral resolution and horizontal misalignment of the sensors. The irradiance is defined with respect to a horizontal area. Thus, if the sensors are tilted with respect to this area, an error is introduced into the measurements.\(^1\) For $\theta_s = 60^\circ$ and a horizontal misalignment of $1^\circ$, this error is 3% for the measured irradiance and about 30% for the layer absorptance. Therefore, an in-flight active stabilization system using aircraft attitude data was implemented for the spectral albedometer. A detailed description of the instrument is given by Wendisch et al. (2001), and measurements are presented by Wendisch (2003), Wendisch and Mayer (2003), and Wendisch et al. (2004).

The albedometer mainly consists of an irradiance measuring unit and a horizontal stabilization system. Two optical inlets (cosine diffuser domes) are mounted on bottom and top of the aircraft fuselage on horizontally stabilized platforms for measuring the up- and downward global irradiance, respectively. The cosine diffuser domes (Meteorologie Consult

\(^1\)The same problem occurs with pyranometer measurements.
GmbH, Glashütten, Germany) provide the cosine weighing for the irradiances. The response of these diffusers depends on the incidence angle of the radiation onto the surface of the domes. At normal incidence, this error is minimal. For other incidence angles, a correction factor must be applied. This correction factor is different for diffuse and direct radiation and is included in the data processing. The stabilization is accomplished by two-dimensional tilt stages for both optical inlets. They are driven by servomotors which correct for the changing attitude angles within a range of ±6° inclination of the aircraft with respect to the Earth’s surface. The attitude angles (roll and pitch) are precisely measured by an artificial horizon system using gyroscopes and a supporting global positioning system (GPS). The signals of this system are used by the servomotors for the horizontal adjustment of the platforms. The accuracy of the leveling in real time is better than ±0.2°.

Each of the optical inlets is connected via fiber optics to a Multi-Channel Spectrometer (MCS) module with a fixed grating, manufactured by Zeiss GmbH, Jena, Germany. The spectral resolution of the MCS modules is 2-3 nm, and the wavelength ranges from 290 to 1000 nm. A similar system was developed at NASA Ames Research Center, California, USA, and is described by Pilewskie et al. (2003) and Wendisch et al. (2004). Its spectral range (300 to 1700 nm) is larger towards the IR. However, it is fixed on the aircraft fuselage. The intensity and wavelength calibration of the albedometer by means of standard lamps and the measurement of the cosine correction factor are described in Wendisch et al. (2002a). Issues of the calibration technique with spectral irradiance standards are discussed by Kiedron et al. (1999).

The measurement error of the albedometer comprises calibration lamp uncertainties, temporal calibration drifts (changes of the calibration throughout a measurement flight), the error in the distance between the calibration lamp and the receiving plane in the detector, coupling of the optical fibers, residual cosine errors after correction, and uncertainties of the horizontal stabilization. The total error is about 6% between 290 and 400 nm and between 770 and 1000 nm. Within 400 and 770 nm, the error is in the range of 4% (Wendisch, 2003). The error of the layer properties T, R, and A is evaluated by Gaussian error propagation.

In addition to the cosine weighed measurements (albedometer), two new sensor heads (AFDM - actinic flux density meter) have been added to the up- and downlooking platforms with isotropic inlet for measuring actinic flux densities. This system is described by Jäkel et al. (2004).

For ground-based irradiance measurements in this work, a MCS module with a spectral resolution of 2.4 nm and a wavelength range from 500 to 920 nm was used which is connected to an optical inlet (cosine diffuser dome) via fiber optics. The optical inlet is adjusted such that it is horizontally aligned with the ground. As the albedometer, it measures the global radiation. The diffuse light can be estimated by shading the sensor from the direct sun.
Chapter 4

Field Campaigns

This chapter introduces the two field experiments and measurements which are relevant for the subsequent chapters. To begin with, the airborne and balloon-borne instrument platforms used for these experiments are presented.

4.1 Instrument Platforms

4.1.1 Aircraft

The airborne measurements presented in this work were performed using a Partenavia P86B, registration D-GERY. This is a two-propeller, unpressurized research aircraft which is rented from Enviscope GmbH, Frankfurt/M., Germany for field experiments. The aircraft speed ranges between 60 and 80 m s$^{-1}$, the maximum operating height is about 4000 m. Maximum flight time is four hours. The aircraft was equipped by IFT with meteorological, microphysical, and radiation instrumentation. The altitude is deduced from static pressure which is measured by a Pitot sonde with a capacitive sensor, giving a precision of approximately ±20 m. Static air temperature and relative humidity are measured by Vaisala sensors which are mounted in a reverse flow inlet. Velocity is derived from dynamic pressure. Geographical coordinates are provided by GPS. The aircraft attitude angles (pitch and roll) are measured by a combination of gyroscopes and GPS.

Cloud microphysical instrumentation

Below the wings of the aircraft, there are two mounting hardpoints for instrument canisters. They are more than 4 meters away from the propellers, where the flow is expected to be undisturbed. The separation between the two positions on either side of the aircraft is more than 8 meters which needs to be considered when analyzing data at high frequency. Within this work, the Fast-FSSP and the M-Fast-FSSP were implemented on this aircraft. Figure 4.1a shows the M-Fast-FSSP and the PVM mounted beneath the left wing; the Fast-FSSP was mounted beneath the other wing. The FSSPs and the PVM-100A sample cloud droplets under ambient conditions. Aerodynamic studies (King, 1984) have shown that stream velocities close to an aircraft fuselage depart between 5 and 10% from free-stream conditions. Shadow zones for particles were evaluated in units of the fuselage radius. King et al. (1984) compared calculations and measurements of the stream velocities around an
aircraft fuselage and studied differences in LWC measurements which arise when mounting FSSPs at different positions. Large errors occur when the instrument is mounted within the particle shadow zone. The FSSPs and the PVM are mounted clearly outside this region on the Partenavia (more than 25 cm below the wings). Norment (1988) examined the combined effect of aircraft and sampling tube flow distortions: Although the FSSP samples under ambient conditions, the sampling tube is an obstacle to the airstream, reducing stream velocities by up to 10% within the sampling tube. The PVM LWC measurements are independent of the stream velocity. As long as the drop size distribution is not perturbed by flow conditions around the aircraft, measurements are not affected. As a further reference for LWC measurements, a Nevzorov hot-wire probe was mounted outside a cabin window (Figure 4.1b). Despite the unusual mounting position, the sensor head is outside the shadow zone (smaller than about 10 cm in the cockpit region). Detailed aerodynamic studies have not yet been made for the Partenavia, the dimensions of shadow zones were estimated from King (1984).

Radiation

The aircraft was equipped with two stabilized platforms with two optical inlets each, for actinic and for irradiance measurements (3.2.2). Figure 4.2 shows the upper platform. The flat dome with cosine diffuser is used for downward irradiance measurements. The other (isotropic) inlet belongs to the AFDM. The ball-shaped support can be turned in two directions for the horizontal stabilization.

The absolute calibration of the albedometer was performed with a standard irradiance 1000 W lamp (traceable to the Physikalisch Technische Bundesanstalt) in the laboratory before and after the field experiments. Addition-
ally, secondary calibrations were performed before and after the flights using various 200 W lamps. In this way, uncertainties due to dis- and reconnecting fiber optical cables were taken into account. The cosine weighing of the individual diffusers was measured in the laboratory. The calibration of the ground-based spectrometer including the measurement of the response of the cosine diffuser was performed in the laboratory.

4.1.2 Tethered Balloon

The balloon-borne measurements presented in this work were performed with a platform suspended on a tethered balloon. The payload platform ACTOS (Airship-borne Cloud Turbulence Observation System) was developed at IfT (Siebert et al., 2003). The balloon system MAPS-Y (Mobile Automatic Positioning SYstem) is owned and operated by the German army. The balloon was filled with hydrogen, the useable payload was about 100 kg. The maximum operating height is 1200 m. Photographs of the balloon in operation with the suspended payload and of the front part of the platform with instrumentation are shown in Figure 4.3. ACTOS is equipped with standard meteorological instruments, and several high resolution sensors for turbulence measurements: an ultrasonic anemometer for three-dimensional wind speed, an ultrafast thermometer (UFT), hygrometers (Lyman-alpha; Vaisala) for measuring relative humidity, and a GPS-based navigation system. A CPC was added for aerosol particle measurements and a PVM-100A makes high-resolution LWC measurements. A detailed description of the instrumentation is given by Siebert et al. (2003). Within this work, the M-Fast-FSSP was added to the payload.
INSPECTRO (INfluence of clouds on the SPECtral actinic flux in the lower TROposphere) is a European project aimed at a better understanding of tropospheric photochemistry under cloudy conditions. The properties of the three-dimensional field of actinic flux densities are studied for some selected cases as a base for the development of one-dimensional parameterizations to approximate the typical features of the radiation field, which can be implemented in chemistry models. Broken cloud scenarios are a particular challenge for the understanding of complicated radical reactions, because there are still open questions about the influence of spatial variability in the radiative field.

In September 2002, the field experiment INSPECTRO-2002 was held in Norwich on the coast of East Anglia, UK. Figure 4.4 shows a map of the area with the four ground stations where spectrometers performed measurements of actinic flux densities and of irradiances. Additionally, highly resolved chemical measurements of radicals were performed by the University of East Anglia at M1. At the same station, a mobile lidar system (VELIS: VEhicle mounted Lidar System, run by the Institute for Atmospheric Research, Rome) was situated to measure vertical profiles of aerosol properties, and for the estimation of cloud base height and cloud fraction. All ground-based radiative instruments including the IfT ground-based spectrometer were intercompared a week ahead of the campaign and traced to a standard ground-based instrument. A more detailed description of the aims of INSPECTRO and first selected results are presented by Kylling et al. (2004).

Four aircraft equipped with instrumentation for microphysical, chemical, and radiative measurements were operated from Norwich airport. The IfT Partenavia performed 11 flights, two of which were conducted under clear-sky conditions, and six under broken cloud conditions. Out of three overcast boundary layer cloud situations, partly with cirrus above, two cases were selected for further analysis in this work: In section 4.2.1, an overcast boundary layer cloud case with no cirrus above (September 14, 2002) is discussed. Data from this day are used for radiative transfer modeling. On September 15, 2002 (section 4.2.2), the new M-Fast-FSSP was flown in parallel with the Fast-FSSP, the PVM-100A, and the Nevyzorov probe. There was an overcast boundary layer cloud as on the previous day, but with some cirrus above. The data from this day is used for intercomparison of the microphysical instruments.

Figure 4.4: Flight chart of the measurement area. The aircraft were based on Norwich airport at the bottom of the map. Stations for ground-based measurements are marked by circles M1 through M4. T1 through T3 mark the edge points of the preferred flight pattern.
4.2.1 Overcast Boundary Layer Cloud, No Cirrus Above

On September 14, 2002, a stable overcast stratocumulus layer was measured between 550 and 1000 m. No cirrus was observed. The photographs shown in Figure 4.5 show the cloud top structure (view from above, on the right), and the situation below the cloud cover (view from below, on the left, during an approach to Norwich airport).

Figure 4.6 shows the flight track of this day. Starting from Norwich airport (N), the aircraft measured the profile #1. Subsequently, a triangle above the cloud layer at 1600 m was flown. Then the aircraft descended into the cloud layer to about 780 m and measured a horizontal cloud section (#2). The positions when entering and leaving the cloud are marked #2S and #2E, respectively, and the beginning and the end of the horizontal section by #2CL. The aircraft was within the cloud layer for 1 1/2 triangle (about half an hour). After this leg,
Figure 4.7: September 14, 2002: a: Time series of airborne up- and downward irradiance measurements at $\lambda = 500$ nm and ground-based measurements for the same time interval, downward irradiance refer to a SZA of 55$^\circ$ (dotted line); b: Altitude - thick sections denote cloudy parts. Open squares: overpasses at station M1 (position of the ground-based instrument).

A triangle was flown above the cloud layer at about 2900 m. Leaving the measurement area, a so-called low overshoot was performed over Norwich airport, and profiles #3a (descent) and #3b (ascent) were measured. Finally, #4 was taken up before landing at Norwich airport.

Figure 4.7 shows the time series of irradiance measurements (a) and of the flight altitude (b). The thick sections in (b) mark cloudy sections ($LWC > 0.05\ g\ m^{-3}$). The thick solid line in (a) shows the downward irradiance at the station M4 at 500 nm wavelength. The downward and upward triangles show the airborne measurements of down- and upward irradiance. There is a slight diurnal pattern in $F^\downarrow$. The maximum of the downward irradiance was measured around noon. The up- and downward irradiance measurements were refered to one SZA at about 10 h UTC ($\theta_s = 55^\circ$) by applying the correction

$$F_{\cos} = F \frac{\cos(\theta_s = 55^\circ)}{\cos(\theta_s)}$$

(4.1)

to the data. The downward irradiance corrected by this way is shown as dotted line in Figure 4.7a. It is nearly constant over the whole flight period when staying above the cloud layer. Minor remaining fluctuations can be explained by atmospheric inhomogeneities, aircraft contrails or by malfunctions of the horizontal leveling system. The peaks at UTC=11.3 and UTC=11.6 cannot entirely be explained. The variability of the upward irradiance is much higher. Variations are caused by the variable cloud structure below, and by the surface albedo. However, within and above the cloud layer, the surface has only a minor impact.
Figure 4.8: Structure of the horizontal in-cloud flight leg #2 - LWC and up- and downward irradiance measurements at $\lambda = 500$ nm.

During the in-cloud leg, the variability of $F^\downarrow$ and $F^\uparrow$ is caused by the cloud structure above and below. This leg is enlarged in Figure 4.8. The upper line are LWC measurements; the open symbols show the measured irradiance ($F^\downarrow$: triangle down, $F^\uparrow$: triangle up). The gaps in the irradiance measurements occur when the horizontal stabilization was not able to level the platform.

The downward irradiance is related to the LWP above the measurement altitude. In this case, integrating the LWC in the vertical is not required because the LWC itself correlates partly with the measured irradiance. This is shown in Figure 4.9. Poor correlations between the LWC and the irradiances are caused by inhomogeneities in the vertical structure and by a varying cloud top height.

From the in-cloud measurements, some typical scales can be found: A short range scale is about two minutes ($\approx 0.03$ h). This can be seen from the irradiance and LWC measurements (Figure 4.8), especially between UTC=10.7 and UTC=10.8. This corresponds to about 8 km (true air speed, $TAS \approx 70$ m s$^{-1}$).

Figure 4.9: Correlation plot between $F^\downarrow$ and LWC for the in-cloud leg.
The thermodynamic and dynamic vertical structure of the cloud layer is illustrated in Figure 4.10. The temperature profile shows an inversion over the measurement area between 900 m and 1100 m. Astonishingly, the inversion height was found at about 2000 m for one profile measurement (#2E). A radio sounding launched at Nottingham (latitude=53°, longitude=−1.25°) at UTC=12.0 agreed with the airborne measurements with the low inversion height. The condensation level measured by the sounding was at 920 m. The wind direction varied between 10° and 40° (NNE to NE). Thus, clouds were moving landwards. The wind speed was not measured by the aircraft. The sounding gave 4 m s\(^{-1}\) at the surface and about 9 m s\(^{-1}\) above 1100 m.

Figure 4.11 shows profiles of the LWC and of the downward irradiance measured at 500 nm. For LWC measurements #1 (a) and #3b (b), adiabatic profiles have been calculated from (2.5). The measurements in #3b are only slightly below the adiabatic values. The

![Figure 4.10: Temperature profile measured by aircraft (solid line) and from a sounding at Nottingham (closed circles). Open squares: Wind direction from sounding.](image)

![Figure 4.11: Vertical profiles for September 14, 2002, of LWC (a, b) and F\(\downarrow\) (c). The straight lines are adiabatic profiles for #1 and #3b.](image)
deviations from the adiabatic LWC, for example above 800 m in #1, are probably due to horizontal rather than vertical cloud inhomogeneities, since the aircraft samples the cloud along a slant path rather than flying vertically. The cloud top varies between 970 m and 1070 m. The cloud base is between 540 m and 610 m. For #4, a small cumulus parcel was crossed at 500 m. The profiles measured at various positions throughout the measurement area reflect only a part of the overall spatial variability of the LWC at a fixed altitude while the horizontal part of leg #2 covers a whole triangle at one altitude which is seen in (a) between 770 and 780 m.

The downward irradiance for #3b (c) has a high variability near cloud top. This is due to geometrical cloud top variability which causes a varying cloud optical thickness above the aircraft position. Some values below the average cloud top height are higher than $F_\downarrow$ above the cloud layer. These enhanced values occurred while the aircraft was flying in cloud free sections near cloud top, which can get reflections from neighboring cloud interfaces. In this case, enhanced values were measured down to 70 m below average cloud top height.

### 4.2.2 Overcast Boundary Layer Cloud, Cirrus Above

As on the previous day, there was a stable stratus layer on September 15, 2002. However, there were cirrus clouds coming in from north. This case was used for intercomparison of the microphysical probes because the new M-Fast-FSSP was mounted in parallel with the Fast-FSSP, the PVM-100A, and with the Nezorov probe.

Again, a triangular flight track was flown. Ten profiles were measured. Figure 4.12 shows the time series of the flight altitude. Cloudy section are marked with closed circles. All profiles except #10 were flown within the measurement area. The mean cloud base (1350 m) and top (1700 m) height are displayed as dotted lines.

An attempt to classify the vertical LWC profiles with respect to the position where they were measured is made in Figure 4.13. In the western legs of the triangular pattern (a), the cloud top is between 1650 m and 1700 m. Cloud base is at the constant level of 1350 m for profiles #2, #5 and #7. Above 1600 m, the LWC of the profile #9 resembles the other western profiles. The jump in #9 at this height occurs when the aircraft comes in from the sea. When starting the ascent over sea, the LWC values are much lower. This profile is also
plotted with the profile #4 (b) which was entirely measured over sea. The cloud top of this profile is shortly above 1650 m as on the western legs. The cloud base of both #4 and #9 is at 1400 m. The values of the LWC are smaller than for the profiles measured in the west. Profile #10 was measured in the southeast of the measurement area. The descent was very flat, and in the end, some cumulus clouds were hit. On the legs measured in the east (c), cloud base and top are lifted by 50 m with respect to the western legs. The cloud base is at 1400 m as over sea, and the cloud geometrical thickness is 350 m as over the western legs.

4.3 BBC-2003 - Balloon-Borne Measurements

In September 2001, BBC-2001 (BALTEX Bridge Campaign) was held near Cabauw (latitude=52.0°N, longitude=4.9°E) in the Netherlands as a joint field experiment of the European CLIWA-NET (cloud liquid water network) and the German 4D-CLOUDS project.

The 4D-CLOUDS project aims at studying the effects of cloud inhomogeneities on transport and exchange processes in the atmosphere. During BBC-2001, ground-based, satellite, airborne, and balloon-borne cloud measurements were combined to provide a realistic characterization of 3D cloud fields. Solar radiation was measured by a variety of ground-based and airborne instruments. The remote sensing instruments were intercompared and, where possible, validated with airborne measurements. Details about the instrumentation and some of the results of BBC-2001 are presented by Crewell et al. (2004). A second campaign, BBC-2003, was held at the same place in May 2003.
IfT contributed airborne measurements of cloud microphysical properties and radiation with the Partenavia aircraft for both BBC-2001 and BBC-2003. Within this work, vertical profiles of cloud LWC and effective radius were taken to validate remotely sensed profiles of cloud microphysics (Crewell et al., 2004). Furthermore, the tethered balloon system MAPS-Y (see section 4.1.2) was used by IfT during both campaigns. The M-Fast-FSSP was first used on the platform during BBC-2003.

![Graph showing altitude and concentration over time]

Figure 4.14: Time series of the altitude, drop concentration measured by the M-Fast-FSSP, and of the LWC, measured by the PVM. Cloudy sections are marked by closed circles.

The balloon was operated on ten days. In this work, measurements from May 22, 2003, are used. Figure 4.14 shows the time series of the two ascents and descents. At the left scale, the altitude is shown. The closed circles indicate the cloud layer (PVM LWC above 0.05 g m\(^{-3}\)). The cloud is located between about 250 and 1050 m (horizontal lines). It was composed of two layers. The lower part (limited to the boundary layer) shows a high cloud drop concentration, measured by the M-Fast-FSSP (right scale). Above the interface at about 640 m, the drop concentration decreases significantly.
Chapter 5

Development and Application of the New M-Fast-FSSP

In this chapter, the development of the new M-Fast-FSSP including its predecessors is described in chronological order. First, in section 5.1, the FSSP-100 is introduced, and its principle of operation and shortcomings are explained. Second, in section 5.2, the development of the follow-up version, the Fast-FSSP, is motivated, and the advantages with respect to the FSSP-100 are discussed. Although many of the problems with the FSSP-100 have been solved with the Fast-FSSP, there remained some problems which motivated the development of the new M-Fast-FSSP within this work (section 5.3). In section 5.4, some applications of the M-Fast-FSSP are presented, and for two measurement cases from two field experiments, data are compared with measurements from existing microphysical instrumentation. Parts of this section have been published (Schmidt et al., 2004).

5.1 Principle of Operation of the FSSP-100

The FSSP-100, manufactured by Particle Measuring Systems (PMS, Boulder, USA), was developed by Knollenberg (1976) and is described in detail by Knollenberg (1981) and Cerni (1983). In the following, its principle of operation is summarized and shortcomings of the probe are discussed.

5.1.1 General Setup

The optical setup of the FSSP-100 is shown in Figure 5.1. A laser beam is focused onto the center of a sampling tube (1) by lens system L1. It illuminates drops passing through the tube with the airstream. The forward scattered light is redirected by a prism (2) with mask (3), collected by the lens system L2 (4), and focused onto a beam splitter prism (5). The so-called dump spot (3) stops the direct laser light. The beam splitter prism distributes the light among the two circular photodiodes 'Signal' (S) and 'Annulus' (A). 'Signal' is used for sizing the drops. The 'Annulus' detector is masked such that only light within an annular region around its center is detected. It is used to define the length interval along the laser beam from which drops are used to accumulate the size distribution. The voltages of the detectors are processed by analogue electronics which is described by Dye and Baumgardner.
Figure 5.1: Setup of the FSSP-100: (L1) lens system for focusing the laser beam onto the center of the sampling tube (1). (2) Prism for redirecting scattered laser light. The direct laser beam is obscured by mask (3). (4) Collecting optics with lens system (L2) for focusing scattered light onto beam splitter prism with 'Signal' (S) and masked 'Annulus' (S) detector.

(1984). The voltages are amplified and the maximum of the 'Signal' voltage is detected as a drop moves across the laser beam. Moreover, the transit time of the drop through the laser beam is determined.

The helium-neon gas laser (wavelength \( \lambda = 632.8 \) nm) supplies a power of 5 mW and has multiple transversal Gaussian modes. The lens system L1 is adjusted such that its focal point and thus the minimum laser beam waist and maximum light intensity is in the center of the sampling tube. With growing distance from the focal point of L1 along the laser beam axis (\( x \)-axis in Figure 5.1), the beam waist increases, and the light intensity decreases. Measurements of the intensity distribution across the laser beam were performed by e.g. Baumgardner and Spowart (1990). Overall, it decreases towards the beam edges (along \( y \)- and \( z \)-axis in Figure 5.1). In order to prevent an underestimation of the size of droplets passing through the edges of the laser beam, the sampling area is restricted to a region of homogeneous light intensity (see 5.1.3): The valid length interval along the laser beam is defined by the depth of field (DOF) selection by comparing the 'Signal' and 'Annulus' voltage for each drop. Across the laser beam, the velocity acceptance ratio (VAR) is used to reject drops which have a shorter transit time than the average DOF accepted drops through the laser beam.

For the accepted drops, one out of fifteen size channels is attributed to the maximum 'Signal' voltage by using a pulse height analyzer (PHA). The instrument has four switchable drop diameter ranges (2-47 \( \mu m \), 2-32 \( \mu m \), 1-16 \( \mu m \), 0.5-8.0 \( \mu m \)). The electronic amplification factors of the photodetector voltages and the threshold values of the fifteen channels of the PHA are preset by the manufacturer for each of the four ranges. The PHA voltages for the respective diameters are calculated by Lorenz-Mie theory which describes the response of the instrument. In practice, the two fine size ranges are not used because the counts in the
lowest channels are strongly affected by electronic interferences.

The valid drops per size channel and per accumulation time interval (preset by the user) are counted by the electronics. While processing one drop, the probe cannot be retrigered. If a new drop arrives in the laser beam during this time, it is not counted. This electronic dead time ranges from about 2 to 6 µs, depending on the status of the drop. A short dead time applies if the drop is rejected. Otherwise, the 'Signal' voltage is analyzed by the PHA which requires a longer processing time.

5.1.2 Response of the Instrument

The light scattered by a spherical drop \( P_{\text{sca}} \) [W] is calculated by Lorenz-Mie theory (e.g. Bohren and Huffman, 1983) which has to be applied if the scattering object has about the same size as the wavelength of the scattered light. If the incident light can be approximated by a planar wave, \( P_{\text{sca}} \) is the product of the scattering cross section \( C_{\text{sca}} \) [m²] of the drop and the incident light intensity \( I_0 \) [W m⁻²]:

\[
P_{\text{sca}} = C_{\text{sca}} I_0.
\]

For the forward collection angles of the FSSP-100, the partial scattering cross section \( C_{\text{sca}}^{\Delta \chi} \) is used. The angular range \( \Delta \chi \) is determined by the geometry of the probe. The inner collection angle is defined by the diameter of the dump spot (3 in Figure 5.1) on the prism, the outer by the diameter of the collecting optics (4). Usually, \( \Delta \chi = [3°, 13°] \).

A numerical extension of the scattering theory to non-planar waves has been developed by Lock (1993). Within the size range of the instrument, the measured drops are spherical. Corrections for non-spherical drops (Asano and Sato, 1980; Bohren and Coh, 1985) are usually not considered. Likewise, impurities are in general neglected, and the refractive index of pure water is used for numerical calculations of the response of this instrument (Wiscombe, 1980). Under these conditions, the scattered light \( P_{\text{sca}} \) only depends on drop size, on the incident light intensity \( I_0 \), and on the angular collection range \( \Delta \chi \).

The scattering cross section of water drops for an angular range from 3° to 13° and for the wavelength of 632.8 nm is plotted in Figure 5.2. The logarithmic plot shows that the signal ranges almost over three orders of magnitude. The local maxima and minima of the curve can be explained by Lorenz-Mie theory: The drop size and the wavelength determine what type of standing waves are resonant in a drop. The intensity of the scattered light depends on the varying superposition of these waves with drop size. As a consequence, several diameters have the same scattering cross section. For small drop sizes, the Lorenz-Mie theory can be approximated by Rayleigh scattering (\( C_{\text{sca}}^{\Delta \chi} \propto D^6 \)); for large drop sizes, geometric optics (\( C_{\text{sca}}^{\Delta \chi} \propto C_{\text{geom}} \propto D^2 \)) applies.

The inset in Figure 5.2 shows a linear plot of the scattering cross section of the probe for two different refractive indeces \( \nu \) (water: \( \nu = (1.33, 0i) \), solid line; glass: \( \nu = (1.56, 0i) \), dashed line). These response curves (Mie-curves hereafter) are used for the calibration of the instrument.
Figure 5.2: Response of the FSSP-100: Partial Scattering Cross Section for the angular range of the FSSP-100 (3° to 13°) as a function of the drop diameter (logarithmic plot). The dotted lines show the Rayleigh approximation ($D^6$) and geometrical optics ($D^2$). Inset: Linear plot of the Scattering Cross Section for two different refractive indices.

5.1.3 Definition of the Sampling Area and Volume

The definition of the sampling volume is needed because of the inhomogeneity of the light intensity within the laser beam. Drops passing through regions with low light intensity would be undersized and must therefore be excluded from the measurement of the size distribution. Two methods are applied in the FSSP-100: The depth of field (DOF) criterion is used for rejecting drops passing outside the valid length interval along the laser beam ($x$-direction in Figure 5.1). Across the laser beam ($z$-direction), drops passing through the laser beam edges are rejected using the velocity acceptance ratio (VAR). Only drops within the region where both criteria are valid (sampling area $A_v$) are used for accumulating the size distribution.

In order to define the DOF, the voltages of the two detectors are compared for each drop. Figure 5.3 shows the voltages which are obtained when moving a scattering object along the laser beam axis. The optical system on detector side (L2) is designed such that if a drop crosses the laser beam at the focal point of the lens system L1, its image is sharply projected onto the detector plane. Otherwise the image is blurred, and the larger the distance between the focal point of L1 and the drop along the laser beam axis, the larger is the outer diameter of the blurred image on the detector plane.

This is demonstrated by Figure 5.3. The maximum of the 'Signal' voltage is found when the drop (or pinhole) is in the center of the sampling tube (about 9 mm on the relative length scale of Figure 5.3). In this case, the image is sharply projected onto the detector plane, and the mask on the 'Annulus' detector obscures the image completely.
Therefore, the 'Anulus' voltage has a minimum. In Figure 5.3, the voltage does not vanish at this point because the probe optical system was badly aligned, such that a part of the scattered light could be detected by 'Anulus'. The plateau for the 'Signal' voltage from about 7.5 to 9.5 mm corresponds to the region where the light intensity is homogeneous along the laser beam. At the limits of this plateau region, the outer diameter of the blurred image surpasses the mask edges of the 'Anulus' detector, and the light incident onto the annular region around the mask is detected. Outside the homogeneous region, the laser light intensity decreases. The outer diameter of the image on the detector plane gets larger than the diameter of the photodiodes, and only a portion of the scattered light is detected. The 'Anulus' voltage is stronger amplified than the 'Signal' voltage, such that its maxima are higher than the maximum of 'Signal'. The valid length interval (DOF) is defined by the intersection points of the curves. If 'Signal' is larger than 'Anulus', the drop is used for the accumulation of the size distribution, otherwise it is rejected.

Across the laser beam, the velocity acceptance ratio (VAR) can optionally be used. Drops passing through chords near the edges of the laser beam have a shorter transit time than the average transit time. Only DOF-accepted drops with a longer transit time than the average are accepted. By this way, about half of the laser beam cross section is excluded from the valid region used for drop sizing (VAR ≈ 0.5).

The size of the sampling volume \( V_s \) is obtained by multiplying the sampling area \( A_s \), the drop velocity \( v_0 \), and the counting accumulation period \( \Delta t \):

\[
V_s = A_s v_0 \Delta t, \tag{5.2}
\]

where the sampling area \( A_s \) normal to the stream velocity \( v_0 \) is obtained by multiplying the length of the DOF with the beam waist \( w_0 \). If the VAR selection is used, this value must be multiplied with the velocity acceptance ratio which can be measured or calculated theoretically. The DOF has to be measured for all four size ranges. As shown by Dye and Baumgardner (1984), it is slightly size-dependent. Moreover, the measured length depends on the type of scattering object.

From the counting rate \( n_d \) of drops within \( V_s \), the drop concentration \( N \) is derived from

\[
N = \frac{n_d \Delta t}{V_s} = \frac{n_d}{A_s v_0}. \tag{5.3}
\]

Alternatively, the drop concentration can be calculated by dividing the total drop number \( n \Delta t \) by the sensitive volume of the laser beam \( V_s \).
The number size distribution $dN/dD$ is obtained by dividing the number of valid drop counts per size bin and measurement period $n_i \Delta t$ by $V_s$ and the size bin width $\Delta D_i$:

$$\frac{dN}{dD} = \frac{n_i \Delta t}{V_s \Delta D_i} = \frac{n_i}{A_s v_0 \Delta D_i}.$$ (5.4)

Both $A_s$ and $\Delta D_i$ are size-dependent. The main error source for FSSP-100 measurements is $A_s$ for which Baumgardner and Spowart et al. (1990) give a measuring error of 15%. Coincidences (section 5.1.5) cause an underestimation of the counted drop rate. For the drop velocity $v_0$, the true air speed (TAS) around the aircraft fuselage is used.

### 5.1.4 Size Calibration

The calibration of the FSSP-100 is described by Cerni (1983). The theoretical response curve as calculated from Lorenz-Mie theory attributes the partial scattering cross section to the size bins. The voltage corresponding to a partial scattering cross section is obtained by multiplying $C_{\text{Mie}}^{\Delta \lambda}$ with a fixed factor which is determined by the optical setup and by the electronic amplification of 'Signal'. The size bin threshold voltages and hence the shape of the Mie curve (see inset of Figure 5.2) are stored in the PHA for the four size ranges.

If the probe is optically mis-aligned, or optical surfaces are contaminated, the voltage corresponding to a diameter deviates from the manufacturer’s settings. The laser or electronic setup is also a possible source for a different response of instrument. Therefore, a calibration with glass beads of known size is performed. Considering the different refractive indices of the glass beads with respect to the water drops, an equivalent water drop diameter is deduced from the respective Mie curves. The amplification of the 'Signal' voltage is then adjusted such that the output of the PHA corresponds to the preset diameters. Alternatively, if the electronic amplification is not changed, corrected diameters are attributed to the PHA channels by rescaling the response curve (Cerni, 1983; Dye and Baumgardner, 1984).

The Mie curves which are used for the preset manufacturer’s calibration in the PHA do not consider the laser beam inhomogeneities. Hovenac and Lock (1993) calculated a modified response curve taking into account the multimodal structure of the laser. Hovenac and Hirleman (1991) presented an alternative way to glass bead calibration by using rotating pinholes of known diameter. This method allows to check the response of the probe when placing the scattering object at various positions in the laser beam. A further application of this method is to test the performance of the FSSP-100 when varying the transit velocity through the laser beam. Cerni (1983) has already stated that the drop diameter is underestimated when the velocity exceeds some threshold value. This is due to the analogue electronics of the probe and was further investigated by Baumgardner and Spowart (1990) who measured the electronic response times and suggested a correction scheme.

Wendisch et al. (1996) presented a calibration using a water drop generator which is based on a vibrating needle. A conversion of refractive indices is not required because the calibration is performed with water. Problems occur with the stability and reproducibility of the generated drops.
5.1.5 Shortcomings of the FSSP-100

Coincidences and Electronic Dead Time

If a drop enters the laser beam while the previous drop is still present, the probe is not retrigerred. This is called optical coincidence of drops in the laser beam and is inherent to all single particle counters. In addition, if a drop arrives while the probe is still busy processing a drop signal, that is during the electronic dead time, the new drop is not counted. This is called electronic coincidence. The probability of optical coincidences is dependent on the ratio between the total sensitive volume of the laser beam $V_L$ and the mean droplet spacing, which is the inverse droplet concentration $N^{-1}$. Knollenberg (1981) derived a probability of

$$0.5V_L N$$

for a two-drop coincidence within the sensitive volume from the assumption of a Poissonian distribution. The electronic coincidences are determined by the individual probe characteristics.

The drop rate is underestimated by the FSSP-100 due to a combination of optical and electronic coincidences. Therefore, Cerni (1983) suggested an empirical formula to estimate the true rate $n_{\text{corrected}}$ and hence the true drop concentration from the measurements $n_{\text{FSSP-100}}$:

$$n_{\text{corrected}} = \frac{1}{1 - MAc}n_{\text{FSSP-100}}$$

where $Ac$ (activity) is the portion of time the probe was busy processing drops within the accumulation time interval $\Delta t$. $M$ is a probe-dependent parameter which accounts for the specific time constants and other probe characteristics. The different effects of coincidences for FSSP-100 measurements are discussed in detail by Baumgardner et al. (1985). Brenguier and Amodei (1988) developed an accurate correction scheme considering each effect separately. Especially for large drop concentrations, the corrected drop rate obtained by this scheme deviates from the results from formula (5.6).

Instrumental Broadening of the Size Distribution

Cooper (1988) investigated the effect of coincidences on the shape of the drop size distribution. If two or more drops of different size are simultaneously in the laser beam, the probe counts only one. Its size may be overestimated because the scattered light from the other drops adds up to the light scattered by the counted drop alone. At the same time, the concentration of the small drops is underestimated. Overall, the size distribution is broadened towards large drop sizes. Cooper (1988) suggested a correction algorithm for two-drop events based on the inversion of the matrices describing the probabilities for coincidences of the different types.

A broadening towards small size caused by laser beam inhomogeneities is reported by Baumgardner and Spowart (1990), Kim and Boatman (1990), and Wendisch et al. (1996). Baumgardner and Spowart (1990) developed a correction scheme deducing the undistorted size distribution from the measurements, accounting for the laser profile. However, the temporal variability of the laser modes cannot be modeled which makes an inversion difficult.
Further problems of the probe are mainly connected with the probe electronics: (1) The time interval for the accumulation of the size distribution is set by the user before the measurements. Therefore, the resolution of the measurements cannot be increased afterwards. (2) The VAR module is configured for a fixed true airspeed. This electronic component is very sensitive to changes in the velocity. (3) The size of the DOF depends on the drop velocity. (4) The electronic noise of the partly unshielded housing can introduce mis-sizing. Spikes in the 'signal' voltage can cause artificial counts or alter the DOF.

In principle, the instrument can only be applied for measurements of liquid water drops. Gardiner and Hallet (1985) reported that the concentration is overestimated by a factor of up to five in the presence of ice particles because the DOF is increased for ice crystals. In contrast, Gayet et al. (1996) found that the measurements are still reliable for small ice crystals and suggested corrections to the response function of the probe. Own ground-based measurements with the FSSP-100 (Henning et al., 2002) indicate that the measured (ice) water content is lower than measured by reference instruments. This can also be caused by wind ramming of the probe (Wendisch, 1998).

## 5.2 Development of the Fast-FSSP

### 5.2.1 Motivation

Measurements with the FSSP-100 need to be corrected for coincidence events. One way to estimate the true drop rate and concentration from FSSP-100 measurements is using (5.6), suggested by Cerni (1983) and generalized by Baumgardner et al. (1985). Another option is using the coincidence equations in Brenguier and Amodei (1988). For these corrections, auxiliary parameters such as the activity of the probe are needed.

An independent way to determine the concentration which is not biased by coincidences has first been presented by Baumgardner (1986). The rate $n$ of drop arrivals in the sensitive volume $V_L$ of the laser beam is deduced from the series of interarrival times between the drops. If the drops are randomly distributed in space, the Poisson statistics can be used to calculate the probability of the interarrival time $t_i$:

$$p(t_i) = e^{-nt_i}.$$  \hspace{1cm} (5.7)

When plotting the frequency distribution of drop interarrival times $p(t_i)$ logarithmically as a function of $t_i$, the slope corresponds to the drop rate $n$. This method requires to measure the individual drop interarrival times. The FSSP-100 data acquisition provides the accumulated counts for the preset interval $\Delta t$ only. Therefore, Baumgardner (1986) introduced a particle spacing monitor (PSM) recording drop size and arrival time for each drop passing the laser beam. Moreover, a flag indicates whether the drop has passed through or outside the sampling volume, or by the edge. However, the analogue circuitry of the FSSP-100 was maintained for the PSM, and the electronic dead-times after each sampled drop were not removed. Using the slope method, fine length scales in clouds could be accessed by Paluch and Baumgardner (1989). Another way to determine the drop rate from the series
of arrival times (compensation method) was suggested by Baker (1992) and is described in detail by Baumgardner et al. (1993).

Various correction procedures are reviewed by Brenguier et al. (1994). Strictly, they give only the same result if the drops are Poisson-distributed in space. This assumption can be tested using the Fishing test which is based on the property that the variance of the Poisson distribution is equal to its mean value. Baker (1992) showed that the variance in real clouds is often larger than expected (super-Poissonian).¹ In particular, deviations become obvious when the length of the sample for which the Fishing test was performed corresponds to some typical spatial scale. This supplies a way to detect fine structures in clouds down to the centimeter scale.

### 5.2.2 Improved Setup of the Fast-FSSP

The Fast-FSSP (Brenguier et al., 1998) was first applied for cloud measurements at the centimeter scale by Brenguier (1993). This instrument measures each individual drop passing the laser beam. The electronic dead-times which had still been present in the PSM-extended FSSP-100 data acquisition system were removed by replacing the analogue circuitry of the FSSP-100 by fast digital components. In contrast to the PSM which stores the arrival time of each drop, the revised system records the drop interarrival times and the pulse durations. In addition, the Fast-FSSP stores the scattering amplitude of each drop with 8 bit resolution rather than the drop size with 4 bit as the FSSP-100. The scattering amplitude is converted to drop sizes when processing the drop data, using the calibrated response curve. Moreover, the detectors have been replaced such that the combined DOF and VAR rejection scheme of the FSSP-100 could be simplified for the new instrument. A flag indicating whether the drop has passed the laser beam within, outside or on the edge of the sampling area is stored for each drop. The optical setup is in principle the same as for the FSSP-100 as shown in Figure 5.1. In particular, the multimodal laser was not replaced. The different detector configuration is discussed in section 5.2.3.

The improvements of the new instrument with respect to the FSSP-100 are discussed in detail by Brenguier et al. (1998). The coincidence equations introduced by Brenguier and Amodei (1988) are simplified for the Fast-FSSP because the dead-times are eliminated. The coincidence correction (5.6) for the Fast-FSSP reads

\[
    n_{\text{corrected}} = \frac{1}{1 - Act_{\text{Fast-FSSP}}} \cdot n_{\text{Fast-FSSP}},
\]

(5.8)

where the probe activity Act is the ratio of the sum of pulse widths \( t_d \) during the accumulation time \( \Delta t \) (defined when processing the data) and the sum of pulse widths and interarrival times \( t_i \):

\[
    Act_{\text{Fast-FSSP}} = \frac{\sum t^i_d}{\sum t^i_d + t^i_i}.
\]

(5.9)

The empirical factor \( M \) accounting for electronic dead-times is not needed. For a high concentration measurement presented by Brenguier (1993), the major part of the coincidence correction is related to variations in the mean pulse width, a parameter which had not been

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¹Malinowski et al. (1994) and Kostinski and Jameson (1999) found that the super-Poissonian variance of the time series of cloud drop measurements can e.g. be caused by turbulent processes.
Figure 5.4: Flow chart of the digital electronic processing circuitry of the Fast-FSSP. Voltages from the two detectors ($U_{\text{sig}}$ and $U_{\text{ann}}$) are digitized by two 8-bit ADC (1) and compared (2). $U_{\text{sig}}$ is then compared with a preset threshold value (3), and the pulse width $t_d$ and the interarrival times $t_i$ are determined (4). While $U_{\text{sig}}$ is larger than the threshold value, the maximum is determined (5).

recorded by the PSM. The effect of the simplified rejection scheme on the drop size distribution and on the frequency distribution of pulse widths is demonstrated in Brenguier et al. (1998) where measurements using the unmodified (FSSP-100) and the modified (Fast-FSSP) detector setup are compared. The size distributions are narrower when using the modified optics, and the pulse width distribution is more homogeneous.

A further advantage of the Fast-FSSP is the increased size resolution which allows to study the broadening of the size distribution for different cloud conditions. The expected width of the size distribution in continental boundary layer clouds is in the range between 0.5 and 5 µm which can be better resolved by the Fast-FSSP. Brenguier and Chaumat (2001) show size distribution measurements in adiabatic cores of cumulus clouds which are considerably narrower than previously measured with the FSSP-100. A comparison between several FSSP-100 and a Fast-FSSP by Burnet and Brenguier (2002) shows not only that the size distributions from the Fast-FSSP are in general narrower than those measured by the FSSP-100, but also that bimodal distributions were detected by the Fast-FSSP where the FSSP-100 measured only one mode. Perrin et al. (1998) simulated the effects of coincidences on the measured drop size distribution using the transfer matrices of the instrument from Coelho (1996). Brenguier and Chaumat (2001) show some comparisons between original, simulated, and measured size distributions.

A flow chart diagram of the digital electronics of the Fast-FSSP is shown in Figure 5.4. The scattering signal is detected by the two diodes 'Signal' and 'Reference' ('Annulus' for the FSSP-100). The voltages $U_{\text{sig}}$ and $U_{\text{ref}}$ are digitized by two 8-bit ADCs (1). Subsequently, 'Signal' and 'Reference' are digitally compared, and a 2-bit-flag is produced which contains the information whether $U_{\text{sig}} > U_{\text{ref}}$, $U_{\text{sig}} < U_{\text{ref}}$, or $U_{\text{sig}} = U_{\text{ref}}$ (2). At the next stage, it is checked whether 'Signal' is larger than the drop detection threshold value (DTV) which can be set by the user prior to the measurements (3). While 'Signal' is larger than the DTV, a counter for the pulse width is incremented for measuring $t_d$ (4), and the maximum of 'Signal' is determined. When 'Signal' falls below the DTV after the drop transit, a counter for measuring the drop interarrival time $t_i$ is initialized and incremented until the threshold is surpassed at the arrival of the next drop (4). All digital components are clocked at 16 MHz. For each drop, the maximum value of 'Signal', $t_d$, $t_i$, and the 2-bit-flag are stored on tape.
Figure 5.5: Schematic explanation of the rejection scheme in x- and z-direction by using two photodiodes with different diameter. The drop is in DOF if it is centered within the sampling volume; otherwise it gets blurred (x-direction, 3) or displaced (z-direction, 4).

### 5.2.3 Definition of the Sampling Area and Volume

The optical system of the Fast-FSSP was modified in order to extend the DOF selection for the laser beam direction used by the FSSP-100 (x-direction in Figure 5.1) to the direction across the laser beam (z-direction), normal to the drop stream (y-direction). In this way, the electronic VAR criterion of the FSSP-100 was replaced by an optical method, and the sampling area $A_s$ is optically defined. This was accomplished by using two photodiodes with different diameter (‘Signal’, 0.8 mm; ‘Reference’, 0.4 mm). The ‘Reference’ detector is not masked as the ‘Anmulus’ photodiode in the FSSP-100. However, this detector was shadowed by a slit for the first version of the Fast-FSSP\(^2\). In the later configuration no slit was used.

Figure 5.5 shows the principle of the rejection schemes in both x- and z-direction. The scattering signal of a drop is projected onto the detector plane (2) by lens system L2 (1). The selection in x-direction (3) works in the same way as for the FSSP-100: If the image is well focused (a), both detectors receive the whole scattering amplitude. The drop image is out of focus if the drop is not placed at the focal point of lens system. The larger the distance of the drop on the laser beam axis to this point, the larger is the outer diameter of the blurred image of the drop on the detector plane (b). Eventually, its size exceeds the diameter of the ‘Reference’ photodiode (c), and the image of the dump spot gets visible (d). If the drop is completely out of focus, the size of its blurred image exceeds both photodiodes (e).

If the drop is centered with respect to the laser beam cross section, it is also centered with respect to the photodiodes (4A). When it is displaced in z-direction, the image is also displaced on the detector plane. For a small displacement (B), the image is still within the borders of the ‘Signal’ diode, while the ‘Reference’ diode detects only a part of the scattered

\(^2\)Similar to the FSSP-300, a modified version of the FSSP-100 for the measurement of aerosol particles.
light. For a large displacement (C), neither the 'Signal' nor the 'Reference' photodiode detects the drop. By this way, the one-dimensional DOF selection criterion is extended to the two dimensions of the sampling area.

In contrast to the FSSP-100, the layout of the photodiodes in the Fast-FSSP requires a more accurate alignment of the optical system. Moreover, the system needs to be checked for alignment before and after each flight, and the sampling area needs to be measured because it is very sensitive to changes in the alignment.

As for the FSSP-100, the size of the sampling volume $V_s$ is obtained by multiplying the sampling area $A_s$, the drop velocity $v_0$, and the counting accumulation period $\Delta t$. The shape of $A_s$ can be approximated by an elliptic cylinder of length $v_0 \Delta t$ with base area $A_s$. The depth of the elliptic sampling area is the DOF length. It is defined by the intersection points of the 'Signal' and 'Reference' voltage curves when moving a pinhole along the laser beam. This is shown in Figure 5.6. The valid region is within the intersection points of the curves where 'Reference' is larger than 'Signal'.

The same applies for the width of the sampling area ($\Delta z$). Hence,

$$A_s = \frac{\pi}{4} \text{DOF} \Delta z. \quad (5.10)$$

The size of the sampling area depends on the ratio of the electronic amplification of 'Reference' and 'Signal', as well as on the diameter of the pinhole and thus on drop size. Therefore, a new method was developed within this work to measure the size dependent sampling volume. Figures 5.7a and b show a contour plot of the 'Signal' (S) and 'Reference' (R) voltage, respectively. The two-dimensional arrays $S(x, z)$ and $R(x, z)$ were determined by moving a 25 $\mu$m pinhole first along the laser beam direction $x$, and measuring $S$ and $R$ on the laser beam axis. Subsequently, the detector voltages across the laser beam $(z)$ were measured at several $x$-positions, and Gaussian functions were fitted to the individual profiles in $z$. The fit parameters were then interpolated along the laser beam. The matrices $S(x, z)$ and $R(x, z)$ were obtained from Gaussian functions across $z$ with the interpolated fit parameters for each individual $x$. This method of measuring the laser beam profile is an alternative way to the measurements by Baumgardner and Spowart (1990). The modal structure of the laser beam is variable, and a different shape is found at different times. The Gaussian approximation of the profile across the laser beam is therefore more appropriate.

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3This is the inverse definition of the FSSP-100 where the DOF is defined where 'Annulus'< 'Signal'.

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Figure 5.7c corresponds to three different electronic amplification ratios between 'Signal' and 'Reference' (thick line: 4:10 - this amplification ratio was used for (a) and (b); inner line: 3:10; outer line: 5:10). For the area inside a contour, 'Reference' is greater than 'Signal' (DOF, extended to two dimensions); on the contour, 'Reference' is equal to 'Signal'. Using the DOF-flag, the size distribution can separately be accumulated for droplets inside, outside, and on the limit of the sampling area.

The size dependence of the sampling area is obtained from the arrays \( S(x, z) \) and \( R(x, z) \). The voltages at each grid point are first converted into channels in the same way as by the electronics of the instrument by multiplying with the conversion factor \( f_C = 255/(V_{255} - V_0) \) of the ADC (\( V_{255} \) and \( V_0 \) are the voltages which are converted to channel 255 or 0, respectively). Subsequently, the arrays are converted into \( \tilde{S}_i(x, z) \) and \( \tilde{R}_i(x, z) \):

\[
\tilde{S}_i(x, z) = f_C (S(x, z) - S_0) f_i + f_C S_0 \tag{5.11}
\]

and

\[
\tilde{R}_i(x, z) = f_C (R(x, z) - R_0) f_i + f_C R_0 \tag{5.12}
\]

with

\[
f_i = \frac{i - f_C S_0}{\max(S(x, z)) - S_0}. \tag{5.13}
\]

With \( \min(S_i(x, z)) = S_0 \) and \( \min(R_i(x, z)) = R_0 \), equations (5.11) and (5.12) ensure that

\[
\max(\tilde{S}_i(x, z)) = i, \quad \min(\tilde{S}_i(x, z)) = f_C S_0, \quad \text{and} \quad \min(\tilde{R}_i(x, z)) = f_C R_0. \tag{5.14}
\]

This is done for each individual channel \( i \). The value \( \tilde{S}_i(x, z) \) is an approximation for the channel into which a drop (counted into channel \( i \) when passing through the center of the sampling area with maximum light intensity) would be counted when passing the sampling area at \((x, z)\). The size of the sampling area for channel \( i \) is the area within the contour defined by \( \tilde{S}_i(x, z) = \tilde{R}_i(x, z) \).

If the electronic offsets of the 'Signal' and the 'Reference' voltage are equal, then the sampling area obtained by this way is not dependent on the channel, because equations (5.11) and (5.12) simply rescale \( S(x, z) \) and \( R(x, z) \). However, the offsets are usually set differently in order to prevent that drops which pass far outside the sampling volume are counted as valid drops.
Figure 5.8: Illustration of the method to calculate the modal response of the Fast-FSSP to a glass bead size distribution with known mean diameter and standard deviation (thin dotted Gaussian with $D_0=20$ µm and $\sigma=2$ µm). A channel is attributed to each diameter of the size distribution through the glass Mie curve (thick line, left scale), and the value of the size distribution is added to the modal response (right scale) for this channel.

5.2.4 Size Calibration

The method for calibrating the Fast-FSSP is illustrated by Figure 5.8. First, the Partial Scattering Cross Section $C^{\Delta\chi}_{\text{scn}}$ (left scale) is related to the 255 channels of the instrument (right scale) through

$$CH(D) = g C^{\Delta\chi}_{\text{scn}}(D),$$

(5.15)

where $CH(D)$ is the Fast-FSSP channel number, and $g$ is the conversion factor from $C^{\Delta\chi}_{\text{scn}}(D)$ to the channel number. In this example, $g$ was set such that channel 255 corresponds to the maximum Partial Scattering Cross Section for glass beads (thick solid Mie response curve) within the expected size range of the instrument (2-50 µm). From a size distribution, the associated Fast-FSSP channel distribution is obtained by summing up the values of the size distribution for the channels which are related to the individual diameters through the Mie response curve. The resulting channel distribution is called the modal response of the instrument. It is multi-peaked because of the structure of the Mie curve.

The simulated modal distributions are compared with the measurements for several glass bead samples with known mean diameter $D_0$ and standard deviation $\sigma$. The fine resolution of the instrument allows to identify and to compare the individual peaks (called Mie peaks) in the modal distribution. Alternatively, Gaussians are fitted to simulated and measured modal distributions, and a linear interpolation between the obtained $D_0^{\text{sim}}$ and $D_0^{\text{mea}}$ is performed for a set of glass bead sizes. The instrument’s calibrated response curve for the glass beads is then

$$CH(D) = gg' C^{\Delta\chi}_{\text{scn}}(D) + g'',$$

(5.16)
where $g'$ is the gain and $g''$ the offset of the linear interpolation. The calibrated response curve for water is obtained by applying the same factors $gg'$ and $g''$ to the Partial Scattering Cross Section of water (dashed Mie curve). After inversion, the curve is fitted by a fifth-order polynomial because it is multi-valued. The range of possible diameters for a measured channel due to the response curve ambiguities is up to 3 $\mu$m. Therefore, the Fast-FSSP sizing error is about 3 $\mu$m for a drop diameter of 50 $\mu$m, and about 1 $\mu$m for 2 $\mu$m.

This calibration method does not take into account the inhomogeneities of the laser beam as proposed by Hovenac and Lock (1993) for the FSSP-100, and will therefore be revisited in section 5.3.5 for the new M-Fast-FSSP. Measurements of the channel distribution in the IfT cloud chamber - the Leipzig Aerosol Cloud Interaction Simulator (LACIS) - have shown that when gradually increasing the drop size, the mean measured channel increases and decreases corresponding to the oscillating Mie response curve for water drops. For high precision measurements of the diameter, the shape of the Mie curve must be taken into account, and the polynomial fit cannot be performed (Stratmann et al., 2004). In this case, the size measurement is much more precise. However, this scheme cannot be used operationally for in-situ cloud measurements, because it requires a rough guess of the expected drop size in advance to trace the oscillations of the Mie curve.

The ambiguities of the Mie curve can also be used to perform an absolute calibration of the Fast-FSSP. This method (Coelho, 1996) is based on the identification of the Mie peaks in the measured channel distribution. Brenguier et al. (1998) demonstrate how the calibration of the instrument varies from flight to flight throughout a campaign by doing a pre-experiment and a post-experiment glass bead calibration, and by identifying the Mie peaks of the measured water drop channel distributions which are accumulated for the whole flight. This method is unique because a calibration of the instrument can be performed with the measurements. However, it will be shown in section 5.3.4 that the shape of the measured channel distribution is not only determined by the Mie curve, but also by the laser beam cross section. Some of the peaks are caused by inhomogeneities of the laser light intensity rather than by the Mie curve. This was not considered by Coelho (1996). Nevertheless, the relative shift of the peaks throughout the flight is a means for correcting the pre- and postexperiment glass bead calibrations.

5.3 The M-Fast-FSSP

5.3.1 Motivation for the Development of the M-Fast-FSSP

Although major shortcomings of the FSSP-100 were already removed with the development of the Fast-FSSP, some problems could not be solved with this instrument. In particular, the instrumental broadening of the drop size distribution caused by the inhomogeneous laser light intensity within the sampling volume, although decreased in the Fast-FSSP, still remained a problem.

Similarly to Politovich (1993), Hudson and Yum (1997), and Miles et al. (2000) for measurements with the FSSP-100, Brenguier and Chaumet (2001) and Chaumet and Brenguier (2001) could not entirely explain the broadening of the size distribution with height above cloud base observed in Fast-FSSP measurements by applying adiabatic drop growth
models. Moreover, it has been doubted whether the shape of the size distribution measured with a Fast-FSSP represents the real conditions. Schmidt (1999) and Schmidt et al. (2000) showed that the shape measured by two different Fast-FSSP probes varies considerably, and that the sampling volume is highly size-dependent, which was previously not considered.

For the Fast-FSSP, the sampling area can only be modified by varying the electronic amplification of 'Reference' before the measurements. Once this parameter is fixed, it cannot be adjusted. Choosing too small sampling volumes results in an insufficient statistical significance of the measurements. Too large sampling volumes result in artificial broadening of the size distribution.

Therefore a modified Fast-FSSP, the so-called M-Fast-FSSP was designed and applied in this work. The idea was to keep the sampling volume variable, such that its size can be selected after the measurements. This is achieved by storing the value of 'Reference' with the maximum of 'Signal' for each drop, and by introducing the 'Reference' Amplification Factor \( m \). By varying \( m \), the size of the sampling volume can be changed after the actual measurement have been taken. This idea does not only allow to balance the requirements of sufficient counting statistics and of a homogeneous laser light intensity within the sampling volume, but also improves the estimates of the natural width of the size distribution unbiased by instrumental broadening (Schmidt et al., 2004). A further advantage of the variable sampling volume in the M-Fast-FSSP is that the effect of the shape of the drop size distribution on bulk parameters such as the LWC, the effective radius, and on the drop concentration can be estimated. Regarding the concentration it will be shown that by choosing a small sampling volume, the effects of coincidences can be significantly reduced, though the distortion of the distribution due to coincidences cannot be remedied. It is inherent to all single particle counters and originates from the whole sensible volume of the laser beam.

### 5.3.2 Revised Setup of the M-Fast-FSSP

The M-Fast-FSSP was designed at IfT. The optical system was copied from the Fast-FSSP. The multimodal helium-neon gas laser as used in the FSSP-100 and in the Fast-FSSP was maintained despite its inhomogeneous light intensity profile and its temporally varying light intensity. Test with a solid state diode laser with Gaussian beam profile failed because this system was not stable enough in terms of wavelength and intensity, although this type of laser generally exhibits much less noise than the helium-neon gas laser. The oscillations of the light intensity from the helium-neon laser produce a noise of about 5-10% of the overall intensity.

The photodetectors and preamplifiers were also copied from the Fast-FSSP. A new design of the detector block containing the beam splitter prism and the 'Signal' and 'Reference' photodiodes was realized with a mechanic tool to center both photodiodes with respect to each other. A good alignment and centered photodiodes are crucial for a well-defined sampling area.

Although the electronics of the Fast-FSSP are well shielded and grounded, electronic noise is taken up by all components. The noise level even increases when operating the digital part and the recording unit of the data acquisition system and thus switching on the clock frequency. The interference from the clock with the analogue part of the electronics is a clear shortcoming of the probe. In contrast to the Fast-FSSP, first-order low-pass filters
rather than third-order filters were used. The purpose of the simplified electronics of the M-Fast-FSSP is to keep electronic noise and interferences with the digital part as low as possible.

The data acquisition including the digital part of the electronics was completely revised for the M-Fast-FSSP. The conditioned photodetector voltages are digitized by two 8-bit ADCs which are clocked with 16 MHz. From the ADC card which is included in the instrument housing, the two signals are transferred to the data acquisition system which is situated in the aircraft cabin or in the rear of the balloon payload. A special low voltage differential signaling (LVDS) bus is used in order to prevent electronic interferences from the aircraft or other sources. On the aircraft, two shielded cables were drawn through the wings with amphenol connectors for standard PMS instrumentation (e.g. FSSP-100). In this way, the new probe can easily be mounted on other aircraft with standard cabling. On the balloon payload, the distance between the probe and the data acquisition system is much shorter, and standard SCSI connectors were used for the LVDS bus.

The data acquisition system consists of a commercial PCI card (manufactured by Hensel Elektronik GmbH, Rostock, Germany) which is plugged into a PC. On the card, the signals are first decoded from the LVDS bus and then processed by a freely configurable field programmable gate array (FPGA). In contrast to the Fast-FSSP with hard-wired signal processing, the new system is much more flexible and can be adapted to the actual application. The processing algorithm is written in VHDL (very high speed integrated circuit hardware description language) and is downloaded to the FPGA every time the instrument is started. This system can be modified and updated without changing the hardware. The FPGA allows a real-time processing of the signals. This is a clear advantage to CPU-based systems. In the latter case, raw signals are processed by the CPU itself rather than by a peripheral FPGA card. With current technology, a stable continuous data flow as needed for a Fast-FSSP can be clocked with 5 MHz at maximum. This is too low for a sufficient temporal resolution of the drop transits. Therefore, the FPGA-based system is currently the state-of-the-art solution of the problem.

Figure 5.9 illustrates the principle of the data acquisition of the M-Fast-FSSP. It shows a short times series of the 'Signal' and 'Reference' voltages which were measured in the laboratory with an oscilloscope when sucking water drops from a nebulizer through the sampling tube with an aspirator. The dashed line at 40 mV corresponds to the detection threshold voltage (DTV) which is set by the user when starting the measurements. Drops with a maximum 'Signal' voltage below this level (e.g. at 400 μs) are not counted. The DTV is set such that it is above the noise level of the signals. In the example shown in Figure 5.9, the DTV is rather high.

Presently, the FPGA is programmed to determine the following parameters from the time series of the two digitized voltages for each of the drops (#1 through #4 in Figure 5.9):

1. The residence time of the drops in the laser beam $t_{d}^{1-4}$ is the time interval for which 'Signal' ≥ DTV.

2. The drop interarrival time $t_{i}^{1-4}$ is the time interval between the previous and the actual drop for which 'Signal'< DTV.

3. While 'Signal'≥ DTV, the data acquisition seeks for the maximum $M_{S}^{1-4}$ and subse-
Figure 5.9: Time series of ‘Signal’ and ‘Reference’ for a laboratory measurement of water drops with an oscilloscope. The pulse widths \( t_{d} \) and interarrival times \( t_{i} \) are defined by the intersection of ‘Signal’ with DTV (40 mV); \( t_{h}^{1} \) is the duration from ‘Signal’ maximum \( (M_{S}^{1}) \) to half maximum value. Out of the four drops, only one is in the sampling area (‘Reference’>‘Signal’).

4. For technical reasons, the time interval \( t_{h}^{1} \) from the maximum to half the maximum of ‘Signal’ is acquired only after and not before the occurrence of the maximum.

5. The value of ‘Reference’ \( M_{R}^{1} \) is determined when ‘Signal’ achieves its maximum value.

For each drop, the 5 parameters \( t_{d}, t_{i}, M_{S}, t_{h}, \) and \( M_{R} \) are transferred from the PCI card to the PC and stored on hard disk. In contrast, the Fast-FSSP stores \( t_{d}, t_{i}, M_{S}, \) and a flag indicating whether \( M_{S} \geq M_{R} \). Table 5.1 compares the parameters which are measured by the Fast-FSSP and the M-Fast-FSSP.

The additional parameter \( t_{h} \) measured by the M-Fast-FSSP is used for a size-independent measurement of the drop velocity (see section 5.3.9). \( M_{R} \) is used to define the sampling area and volume after the measurements and thus to balance the two competing needs of sufficient counting statistics and homogeneity of the laser beam intensity. With the present settings, the FPGA cannot distinguish coincidences. Event #4 in Figure 5.9 is a clear coincidence example with two drops simultaneously in the laser beam. There are two maxima in the ‘Signal’ voltage, and only the larger drop is counted. For this drop, ‘Reference’ is larger than ‘Signal’; it is therefore within the sampling area. The transit time \( t_{d}^{1} \) is lengthened, and \( M_{S}^{1} \) is slightly increased. In this case, the concentration is not underestimated, because the drop which is neglected is not in the sampling area, anyway.
<table>
<thead>
<tr>
<th>Information</th>
<th>Fast-FSP</th>
<th>M-Fast-FSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum 'Signal' voltage $M_s$</td>
<td>8 bit</td>
<td>8 bit</td>
</tr>
<tr>
<td>'Reference' voltage at 'Signal' maximum $M_R$</td>
<td>no</td>
<td>8 bit</td>
</tr>
<tr>
<td>'Signal' $\lesssim$ 'Reference'</td>
<td>2 bit</td>
<td>-</td>
</tr>
<tr>
<td>Drop transit time $t_d$</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Drop interarrival time $t_i$</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Duration from drop maximum to half maximum $t_h$</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 5.1: Parameters stored by the Fast-FSSP and the M-Fast-FSSP for each drop.

Drops #1, #2, and #3 are not within the sampling area. However, if $M_R^2$ is multiplied by a factor $m$ of about 1.5, the rescaled value $mM_R^2$ is larger than $M_s^2$. When applying the DOF-condition from the Fast-FSSP to $mM_R$ and $M_s$, drop #2 is within the sampling area.

### 5.3.3 Definition of the Sampling Area and Volume

The definition of the sampling area (section 5.2.3) is extended for the M-Fast-FSSP by introducing the 'Reference' Amplification Factor $m$.

Figure 5.10 shows how the length of the sampling area is affected by multiplying the 'Reference' voltage with this factor. As in Figure 5.6 for the Fast-FSSP, the 'Signal' and 'Reference' voltage were measured by moving a pinhole along the laser beam. 'Signal' (line with full dots) is kept constant. 'Reference' (open symbols) is varied by applying several amplifications $m$. The measured 'Reference' voltage corresponds to $m = 1.0$ (no amplification). In this case, the length of the sampling area is given by the preset electronic amplification of 'Signal' and 'Reference' as for the Fast-FSSP. Additionally, the curves for $m = 1.2$ and $m = 0.8$ are plotted. For $m = 1.2$ the intersection points of the amplified 'Reference' voltage and the 'Signal' curve are further apart than for $m = 1.0$, and the length of the sampling area is increased. At the same time, the average value of 'Signal' within the sampling area is lower than for $m = 1.0$ because 'Signal' drops off at the borders of the enlarged sampling area. If the 'Reference' voltage is multiplied by a factor of 0.8, the curve cuts out the plateau region of the 'Signal' voltage, and the 'Signal' variability within the sampling area is only 5%. The preset amplification ($m = 1.0$)
results in a 'Signal' variability within the intersection points of the two curves of about 20%, while for \( m = 1.2 \), it is almost 50%. The variability of 'Signal' within the sampling area is one of the major causes for instrumental broadening. Large \( m \)-values result in considerable instrumental broadening. This can be reduced by decreasing \( m \).

Summarizing, the 'Reference' Amplification Factor \( m \) allows to define the sampling area after the measurement. The sampling area is determined by the combination of electronic amplification of both signals and a post-experiment variation of 'Reference'. The 'Reference' Amplification Factor \( m \) is therefore not an absolute measure for instrumental broadening or for the homogeneity of 'Signal' within the sampling area. The post-experiment variation is relative to the preset electronic amplification or changing optical configuration (as well as using a beam-splitter with a different splitting ratio).

The two-dimensional definition of the sampling area works in a similar way as for the unmodified Fast-FSSP where the different electronic amplification ratios shown in Figure 5.7 are set before the measurement. For the M-Fast-FSSP, the same effect can be achieved by varying \( m \) for a fixed electronic amplification ratio after the measurements. In order to account for the different 'Reference' Amplification Factors, the rescaled 'Reference' voltage arrays \( \tilde{R}_i(x,z) \) from formula (5.12) are multiplied with \( m \) before computing the sampling area.

![Graph](image_url)

**Figure 5.11:** Sampling area (a) and 'Signal' homogeneity (b) as a function of \( m \) for channels 50, 100, 150, 200 and 250. (Figure adopted from Schmidt et al., 2004)

Figure 5.11a shows the sampling area for five different channels as a function of \( m \). Its size is growing both with increasing \( m \) and with increasing channel number. The growing size of the sampling area with growing channel number can be explained by the different offset voltages of the 'Signal' and 'Reference' voltage. The 'Reference' voltage \( R \) has a larger negative offset than 'Signal' \( S \). This prevents an unintentional sampling area far outside the center of the laser beam as described by Coelho (1996). The sampling area condition for the M-Fast-FSSP reads

\[
mR \gg S.
\] (5.17)
The 'Signal' homogeneity $H$ is defined as the average value of the 'Signal' voltage within the sampling area, normalized by its maximum value. It is directly calculated from $\tilde{S}_i(x, z)$ (formula 5.11) and $m\tilde{R}_i(x, z)$. In Figure 5.11b, it varies between 0.50 and 0.90; a homogeneity of unity corresponds to a perfectly flat 'Signal' voltage curve within the borders of the sampling area. In this case, all drops of one size would be counted into the same channel independent of their transit position through the laser beam, and no instrumental broadening would occur. A low homogeneity means that a wide range of 'Signal' values occurs within the sampling area, and drops of one size may be counted into lower channels as well. The maximum of the resulting channel distribution is located at a channel which corresponds to the mean value of 'Signal' within the sampling area. The ratio between the maximum value of 'Signal' and its mean value is a measure for the inhomogeneity of the light intensity within the sampling area and indicates how much the maximum of the measured channel distribution is shifted towards small channels. The homogeneity in Figure 5.11b ranges between 0.5 and 0.7 for channel 250 while it attains between 0.8 and 0.95 for channel 50. Hence, the broadening is much more pronounced for large drops than for small ones. This will be confirmed by measurements presented in section 5.4.

5.3.4 Optical Transfer Matrices

The instrumental broadening effect can be quantified by introducing the optical transfer matrices $T_m$ for the M-Fast-FSSP. The matrix element $T_{m,i}^{i,j}$ is the probability that a drop which would be counted into channel $i$ for a homogeneity of unity is counted into the lower channel $j$ due to the laser beam inhomogeneities within the sampling area.

The optical transfer matrices are determined from the arrays $\tilde{S}_i(x, z)$ and $m\tilde{R}_i(x, z)$ which are obtained from the measured $S(x, z)$ and $R(x, z)$ for each individual $i$ as described in section 5.2.3. Subsequently, the values of $\tilde{S}_i(x, z) = j \leq i$ for which $m\tilde{R}_i(x, z) \geq \tilde{S}_i(x, z)$ are counted into a histogram over $j$ for the whole range of $m$-values. Finally, the $j$-histogram for each $m$ and each $i$ is normalized such that $\sum_j T_{m,i}^{i,j} = 1$. The broadened channel distribution $dN/dC_{Ch_m}$ is then calculated from the undisturbed channel distribution $dN/dC_{Ch_0}$ which would be measured for a homogeneity of unity via the matrix multiplication

$$\frac{dN}{dC_{Ch_m}} = T_m \frac{dN}{dC_{Ch_0}}. \quad (5.18)$$

Figure 5.12 shows the probability distributions $T_{m,i}^{i,j}$ for input channel $i = 255$ (monodisperse distribution at 255) and three different 'Reference' Amplification Factors $m = 1.0$ (thick solid line), $m = 1.2$ (dotted line), and for $m = 0.8$ (dashed line). Moreover, the distribution for $i = 180$ and $m = 1.0$ is plotted (thick dashed line).

In general, the broadening is less pronounced for smaller input channels: The minimum output channel for an input channel of 180 is almost the same as for an input channel of 255 (40 and 50, respectively). Varying $m$ changes the shape as well as the width of the probability distribution of the output channels. Higher $m$-values result in a larger and hence more inhomogeneous sampling area. Therefore, the peaks of the distribution for $m = 1.2$ are shifted towards lower channels for $i = 255$ with respect to $m = 1.0$. The distribution for $m = 0.8$ is much narrower than the distributions for $m = 1.2$ and $m = 1.0$. For $m = 0.60$ (not
Figure 5.12: Optical transfer matrix: probability distribution of output channels for two given input channels \(i = 255\) and \(i = 180\), and for three different 'Reference' Amplification Factors \(m = 1.2\), \(m = 1.0\), and \(m = 0.8\).

shown), the width of the probability distribution is only about 20 channels. The resulting mean output channel for \(i = 255\) is 161, \((178, 203)\) for \(m = 1.2\), \((1.0, 0.8)\), converging to 255.

The ratio between the mean output channel and \(i\), and hence the extent of broadening for a given 'Reference' Amplification Factor \(m\) and input channel \(i\) depends on the optical and the electronic configuration of the probe. If the optical system is misaligned, the 'Reference' defines an inhomogeneous sampling area, and hence the small output channels are favored by the transfer matrices. The \(m\)-value is relative to the electronic amplification of 'Reference' and 'Signal'. Changing the electronic amplification also changes the effects of varying \(m\), and different transfer matrices apply.

The optical transfer matrices defined above differ from the transfer matrices which were introduced by Brenguier et al. (1998) for the Fast-FSSP. Their approach is a full description of the Fast-FSSP predicting the channel and transit time distribution from a given drop size distribution and include the effects of coincidences. These were simulated by Perrin et al. (1998) with a Monte-Carlo model. In contrast, the optical transfer matrices account only for the instrumental broadening due to the laser beam inhomogeneities. In conjunction with the Mie response curve, they can also be used to predict the broadened channel distribution directly from the size distribution. An estimation of the transit time distribution was not implemented. The effects of coincidences are not predictable by the optical transfer matrices.

### 5.3.5 Size Calibration

#### Classical Calibration Method

The size calibration described in section 5.2.4 for the Fast-FSSP can be applied in the same way for the M-Fast-FSSP. Figure 5.13 shows the channel (a) and the size (b) distribution
Figure 5.13: a: Channel distribution for 19.9 µm glass beads - the curves with a small number of total counts correspond to a low m-value. The higher m, the more glass beads are considered to be valid, and the further the maximum of the distribution moves towards lower channels. b: Size distribution obtained by applying a calibration to Figure 5.13a for each m separately. (Figure adopted from Schmidt et al., 2004)

for a calibration with 19.9 µm monodisperse glass beads\(^4\). They were sucked through a tube with 0.5 cm diameter which was focused onto the sampling volume. The measurements were then processed with various m-values. Figure 5.13a illustrates the effect of varying size and homogeneity of the sampling area on the channel distribution and its width. While the position of the right wing of the glass bead channel distribution does not vary considerably, the position of the left wing moves towards lower channels for increasing m because more glass bead counts from the edges of the laser beam are accepted. The calibration must be performed for each m-value separately. For a range of glass bead diameters, the measured channel distribution, processed with a set of m-values, is compared with the modal response for glass bead samples with given mean diameter and standard deviation (see Table 5.2 for specifications). The gain and offset for rescaling the Mie response curve (formula 5.16)

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
D_0 [\mu m] & 30.2 & 19.9 & 14.5 & 10.0 & 5.1 \\
\sigma [\mu m] & 2.0 & 2.1 & 1.7 & 1.1 & 1.2 \\
\hline
\end{array}
\]

Table 5.2: Mean diameter \(D_0\) and standard deviation \(\sigma\) for five glass bead samples.

obtained from a linear interpolation between the mean channel of the measurement and of the modal response varies for the different m-values. In this way, a diameter of 19.9 µm is attributed to channel 100 for \(m = 1.4\), while this size corresponds to channel 70 for \(m = 0.75\) (vertical arrows in Figure 5.13a).

\(^4\)manufactured by Postnova Analytik GmbH, München, Germany
Figure 5.13b shows the size distributions $dN/dD_m$. They were obtained from the measured channel distributions through the rescaled Mie response curves for each $m$, and by dividing the counts per size bin by the width $\Delta D_i$ of the bin $i$ and by the size-dependent sampling volume $V_s$. For small $m$-values, $V_s$ is small, and there are only a few counts which are accumulated for the channel distribution. When dividing these two small quantities, a large error is introduced. In this case, the size distributions with $m < m_{\text{max}} = 1.4$ were normalized such that the concentration (integral of the size distribution) is the same as for $m = m_{\text{max}}$, with minimal uncertainty for the sampling area.

New Calibration Method

The new method accounts for both the Mie oscillations and for the inhomogeneities of the sampling area. From the glass bead size distribution $dN/dD$, the modal response $dN/dCh_0$ is calculated using the Mie curve as described in section 5.2.4. Subsequently, the optical transfer matrix $T_m$ is applied to $dN/dCh_0$ to account for the laser beam inhomogeneities within the sampling area: $dN/dCh_m = T_m dN/dCh_0$. The resulting channel distribution is different for the various $m$-values because of $T_m$.

For glass beads with a mean diameter of 30.2 $\mu$m, Figure 5.14 shows the modal response $dN/dCh_0$ (thin solid line), $dN/dCh_{m=1.0}$ (dash-dotted line), and measurements ($m=1.0$, thick solid line). In this case, a first guess of the calibration factors $g'$ and $g''$ (formula 5.16) from the classical calibration was used for the conversion from $dN/dD$ to $dN/dCh_0$. A very good agreement of the shapes of $dN/dCh_{m=1.0}$ and of the measured channel distribution ($m=1.0$) is found. In contrast, $dN/dCh_0$ is far more spiky than the measured channel distribution and does not have the same structure. The knowledge of the individual peaks allows a precise adjustment of the Mie response curve. This is done by linear interpolation as described for the classical method. The procedure was automated within this work to provide the calibration for all desired $m$-values.

Optionally, additive and multiplicative noise can be added (corresponding to electronic and optical noise from the laser, respectively) to correctly simulate the response of the instrument. In Figure 5.14, no noise has been added. The effect of noise is that the slope of both wings of the channel distribution is flattened. Since the noise level is not exactly known, noise is not considered for the calibration. This is justified as long as the noise

---

5 Gaussian with manufacturer’s specifications.
Figure 5.15: Schematic comparison of the new and the classical calibration method: a-c: Classical method, c-e: New method. (Explanations in the text.)

level is of the same range for the calibration measurements and the actual field measurements. The largest differences between the measured and the simulated channel distribution are found at the maximum around channel 200 and for the channels higher than 230 where the measured size distribution has clearly more counts than the simulated one. The first deviation is removed when introducing noise into the simulation while the second deviation persists and is probably due to coincidences. The peak in channel 255 is caused by glass beads exceeding the maximum size bin of the instrument (oversize channel).

**Comparison of both Calibration Methods**

In the schematic overview in Figure 5.15, the new and the classical calibration method are compared. Figure 5.15a-c illustrates the classical method:

Step 1 (a): Using the Mie curve $CH(D)$, the modal response is calculated from a Gaussian size distribution. A mean channel $\langle Ch \rangle^{MOMD}$ around 220 is attributed to the size distribution with $\langle D \rangle = 30 \mu m$.

Step 2 (c): From the measured channel distribution (sketched on the vertical axis: line with closed circles), the mean channel $\langle Ch \rangle^{MEASURED}$ is evaluated for a set of $m$-values (in this case, $\langle Ch \rangle^{MEASURED} \approx 160$).

Step 3 (b): The mean channel of the modal response is plotted versus the measured mean channel for several glass bead sizes. In this example, this has been done for a small
m (open squares) and for a larger m (open circles). The mean channel of the modal response is the same for all m values.

Step 4 (b): A linear interpolation is performed for each of the desired m-values. The interpolation coefficients $g'$ and $g''$ are used to rescale the original Mie curve $CH(D)$ (as for the Fast-FSSP in formula 5.16).

The new method illustrated in Figure 5.15c-e makes use of the optical transfer matrices $T_m$:

Step 1 (d): As for the classical method, the modal response is calculated. Subsequently, it is multiplied with the $T_m$ matrix (vertical arrow). From the resulting channel distribution (line with closed squares), the mean channel $\langle Ch \rangle^{MODTM}$ is calculated for each $m$.

Step 2 (e): The mean simulated channel $\langle Ch \rangle^{MODTM}$ is plotted versus the measured mean channel $\langle Ch \rangle^{MEASURED}$ for several glass bead sizes. In this example, this is shown for only one m-value. Alternatively to comparing mean channels, the individual peaks of the simulated and the measured channel distribution can be compared.

Step 3 (e): A linear interpolation is performed. The interpolation coefficients $g'$ and $g''$ are used to rescale the Mie curve. However, the calibration curve obtained by this way is valid for drops which are only exposed to the maximum laser light intensity. Therefore (c), $T_m$ must be applied to the Mie curve itself (Mie→$T_m$) before rescaling with $g'$ and $g''$. For each diameter of the Mie curve, the mean output channel of $T_m$ (thin solid line with squares) is attributed to the respective channel from the Mie curve (thin solid line).

In the last step for both methods, the rescaled Mie curves are inverted to obtain $D(CH)$, and a fifth-order polynomial interpolation is performed to remove the ambiguities of the resulting calibration curve.

For the classical method, the effects of the laser beam inhomogeneities are implicitly considered by the calibration. The optical transfer matrices are not required. However, it is difficult to compare the measured channel distribution with the simulated modal response because the simulation does not account for instrumental broadening. Especially for large diameters it is impossible to interpret the modes of the measured and the simulated curves, and fitting a Gaussian is the only solution for using the calibration measurements.

With the new method, the shape of the measured distribution is reproduced (Figure 5.14). Therefore the curves can be more easily compared, and it is possible to relate the individual peaks. On the other hand, this method involves the optical transfer matrices which is a problem if $\tilde{S}$ and $\tilde{R}$ are afflicted with large errors. However, the accuracy of the new method can be checked by using the rescaled Mie curve for a secondary calibration. If the new $g' = 1$ and $g'' = 0$, the rescaled Mie curve is consistent with the calibration measurements. Otherwise, the calibration can be repeated until this condition is valid. The coefficients are the same for all m-values because the laser beam inhomogeneities are explicitly considered by $T_m$ and not by the coefficients themselves. The resulting rescaled Mie curve (thick line in Figure 5.15c) should be the same for both methods. In practice, there are some differences between the classical and the new calibration curve, especially for small diameters.
5.3.6 Sampling Area Revisited

The size of the sampling area is the largest error source for FSSP drop concentration measurements. For the FSSP-100, an uncertainty of 15% is given by Baumgardner and Spowart (1990). Brenguier et al. (1998) argue that this error attains even 20% for the FSSP-100 and give an error of 10% for the measurement of the sampling area of the Fast-FSSP. However, they did not consider that the sampling area of the Fast-FSSP is size-dependent. A comparison of drop size distribution measurements with two Fast-FSSP probes (Schmidt, 1999; Schmidt et al., 2000) revealed that even if the total measured drop concentration is equal for the two probes, the shapes of the size distributions may differ systematically. For some channels, a difference up to 50% was found in $dN/dD$ between the measurements of the two probes. This can partly be related to the different opto-electronic configuration and partly to a wrong sampling area.

An alternative new method for determining the size of the sampling area for each individual $m$-value is introduced in the following. It is based on the size of the sensitive area of the laser beam and on the measurements themselves. The number $n_m \Delta t$ of drops which are used for accumulating the size distribution depends on the size of the sampling area $A_s$ whereas the total number $n \Delta t$ of counted drops is related to the sensitive area $A_L$ of the laser beam:

$$\frac{n_m}{n} = \frac{A_s}{A_L}. \tag{5.19}$$

The idea of the new method is to determine the ratio $r(i) = n_m/n$ for as many channels $i$ as possible from the measurements. From (5.19), the sampling area is then $A_s = r(i)A_L$. The sensitive area $A_L$ is the total area of the grid points $(x, z)$ for which $\tilde{S}_i(x, z) \geq DTV$.

Figure 5.16 shows the sensitive volume as a function of the channel number $i$ for a $DTV$ of 23, 26, and 30. The sampling area $A_s$ has been calculated from $A_L$ for $DTV = 26$ by multiplying with $r(i)$. This factor was determined from measurements on September 15, 2002, by attributing $n_m/n$ to the mean measured channel $i$ for each time interval $\Delta t$. The highest mean measured channel for this flight was about 90. Therefore, $r(i)$ was only available up to this channel. For the higher channels $r(i)$ was set to $r(90)$. For this reason, the curves showing the sampling area for the different $m$-values are smooth above channel 90.
The estimated uncertainty of this new method is about 10% which is only slightly lower than for the FSSP-100. The 10% estimated by Brenguier et al. (1998) for the Fast-FSSP are probably far too low. The sampling area which is determined from the old method depends strongly on the shapes of the compared arrays $S_i(x, z)$ and $\tilde{R}_i(x, z)$. The uncertainty is much larger than for the new method because the difference between two error-afflicted quantities is needed (at least 20%). Especially if the sampling area is very small for small $m$-values, the old method does not work. In contrast, only $\tilde{S}_i(x, z)$ is needed to calculate the size of the sampling volume with the new method.

5.3.7 Coincidence revisited

Knollenberg (1981) estimated the probability of two-drop-coincidences per counted drop, $0.5V_Lc$ (formula 5.5), resulting in an underestimation of the total counted drop rate. The size distribution is also affected: Small drops are not counted if larger drops are present in $V_L$, and the size of the counted drops is overestimated, causing a broadening of the size distribution towards larger sizes.

The concentration can either be calculated from the total counted drop rate, dividing it by $V_Lv_0$, or from the rate of valid drops, divided by $V_s(m)v_0$. Consider the last drop (#4) in Figure 5.9 which shows a two-drop-coincidence event. When deriving the concentration from the total drop rate, one count is divided by $V_Lv_0$. The small drop is not seen. When deriving the concentration from the valid drop rate, the count number is divided by $V_s(m)v_0$. In this case, the concentration is not underestimated because the second drop is not valid, anyway. Now consider to increase $m$ gradually until the 'Reference' voltage is amplified such that the second drop would be valid. Because of the coincidence, it would not be counted. Thus, the concentration is only underestimated if $m$ is larger than a certain value.

For concentration measurements, (5.5) must be modified, and $V_L$ must be replaced by $V_L^*(m)$. Note that $V_s(m) \neq V_L^*(m)$; $V_s$ is the sampling volume, a cylinder with base area $C_s$ and length $v_0\Delta t$, while $V_L^*(m)$ is an ellipsoid. Its size determines the probability of coincidences of valid drops. Figure 5.21 shows that using different $m$-values, the concentration determined from the valid drops is indeed higher for small $m$-values. For a very small sampling volume, the concentration measurement should not be affected by coincidences. In this case, however, the measurements are not statistically significant. In turn, deriving the concentration from the total drop rate gives a high statistical significance but a strong underestimation because of coincidences.

The results shown in Figure 5.21 and Table 5.3 show that in contrast to e.g. Knollenberg (1981), coincidences can be reduced when decreasing the sampling volume. They are not related to the size of the sensitive volume, but to an effective sensitive volume $V_L^*(m)$.

5.3.8 Method to Minimize Instrumental Broadening

The instrumental broadening is minimized by gradually decreasing $m$: The width $\sigma$ of the measured size distribution as in Figure 5.13 is obtained by fitting a Gaussian function

$$\frac{dN}{dD} \propto \exp \left( -\frac{(D - D_0)^2}{2\sigma^2} \right)$$

(5.20)
to $dN/dD_m$. $D$ is the diameter; $D_0$ is the measured mean diameter of the size distribution. Alternatively, $\sigma$ can be obtained by calculating the standard deviation for $D_0$ from the size distribution. For laboratory glass bead calibration measurements, Figure 5.17 shows how $\sigma$ changes for four different types of glass bead samples with known mean diameter $D_0$ and standard deviation $\sigma$ when varying $m$ (glass bead specifications see legend in Figure 5.17). The fitted width $\sigma$ is plotted versus the ratio of counts within the sampling volume (valid counts) for a specific $m$ and the valid counts for $m = m_{\text{max}} = 1.40$. This quantity (relative count number) is directly proportional to the sampling volume. Hence, a linear extrapolation to zero counts corresponds to an extrapolation to zero sampling volume with laser beam homogeneity of unity. Above a certain $m$-value, the plot becomes slightly non-linear. Therefore, only $m$-values with minor deviations from the linear relationship are used by the extrapolation program. The results which are obtained when using Gaussians and other, e.g., lognormal distributions as fitting functions are consistent within the range of uncertainty of the extrapolation.

The standard deviation of the glass bead distribution as indicated by the manufacturer is plotted as full symbols at zero counts. Applying the extrapolation from the measurements to zero relative count number gives almost the same value for $\sigma$, except for 19.9 $\mu$m glass beads where the estimated width is 0.6 $\mu$m lower than the standard deviation given by the manufacturer. However, the glass bead sample specifications were not independently tested using a microscope.

For 10 $\mu$m glass beads, the width stays almost constant when gradually decreasing $m$. For the large glass bead sizes, the reduction of $\sigma$ with decreasing relative count number is much

![Graph](image-url)

Figure 5.17: Laboratory glass bead measurements: Fitted width $\sigma$ vs. the relative count number (proportional to the sampling volume - open symbols) for four different glass bead sizes with standard deviation specified by the manufacturer (plotted at zero relative count number - closed symbols). The lines correspond to the extrapolation within the linear $m$-range. Figure adopted from Schmidt et al. (2004).
more pronounced. The instrumental broadening grows with the scattering light intensity and hence with the size of the scattering object. However, the relative broadening, that is the broadening factor caused by the laser beam inhomogeneities divided by the scattering amplitude, is nearly constant. For 30.2 μm glass beads, the maximal width obtained with \( m = 1.40 \) is about 8 μm, while the minimal \( \sigma \) is only 3 μm (\( m = 0.65 \)). Extrapolation to zero relative count number gives a width of about 2 μm which is a factor of four lower than measured with \( m = 1.40 \), and which corresponds well with the manufacturer’s specification.

The presented method is not limited to a monomodal distribution. It can likewise be applied to bimodal distributions. It is also possible to obtain an estimate of the original shape of the glass bead or drop size distribution. For this purpose, a minimum number of valid counts is defined (> 1000 for the 255 channels), and the value of \( m \) is only decreased as long as the valid count number does not fall below this threshold. In this way, the accumulated size distribution is still statistically meaningful.

### 5.3.9 Drop Velocity Measurements

For the correct measurement of the drop concentration and of the LWC, the drop velocity \( v_0 \) has to be known. So far, the true air speed has been used for aircraft operation. The M-Fast-FSSP gives the unique opportunity to measure the drop velocity directly. It is calculated for every individual drop from the measurements by dividing the distance \( \Delta \) from the laser beam center to half maximum (derived from pinhole measurements) by the duration from maximum of ‘Signal’ to half maximum of ‘Signal’ (this parameter is stored for each drop).

![Figure 5.18: Time series of measured wind and drop speed on May 22, 2003. Solid line: Averaged drop speed measured with the M-Fast-FSSP. Averaging time period: 20 s. Dashed-dotted line: Sonic wind speed.](image-url)
This allowed to operate the M-Fast-FSSP on the platform of the tethered balloon system MAPS-Y. No aspiration was applied in order not to disturb the wind measurements. Figure 5.18 shows an example of a time series of the measured wind speed (Sonic anemometer) and drop velocity. The sections without data are drop free intervals. The difference between the two speeds might be due to the uncertainty of the measurement of $\Delta \approx 20\%$, but are more probably caused by the different positions of the instruments: The M-Fast-FSSP was mounted much closer to the body of the platform than the sonic anemometer (see Figure 4.3). The correlation between both instruments was $r^2 \approx 0.85$. In practice, drop velocity rather than the sonic wind speed is used for the calculation of $V_s$.

5.4 Application of the M-Fast-FSSP

5.4.1 Aircraft Measurements

The aircraft measurements during INSPECTRO from September 15, 2002 (4.2.2), were used to intercompare the Fast-FSSP, the new M-Fast-FSSP, the PVM-100A, and the Nevzorov probe.

Figure 5.19 shows the size distributions which were measured for profile #4 at 1500 m near cloud base. The Fast-FSSP measured distribution has about the same shape as the $m=0.9$ distribution measured by the M-Fast-FSSP. Fitting Gaussian functions to these distributions gives a width $\sigma$ of about $2.3 \mu m$. For $m=1.1$ a width of $3.5 \mu m$ is obtained. The peak at $5 \mu m$ is caused by instrumental broadening. Below $5 \mu m$, the size distribution is truncated. Applying the extrapolation scheme results in $\sigma = 2.0 \mu m$. The extrapolated width does not differ much from the measurements of the Fast-FSSP and M-Fast-FSSP for $m = m_{\min} = 0.9$. The value of $m_{\min} = 0.9$ is determined by the minimum valid

![Figure 5.19: Size distributions for profile #4 from September 15, 2002, measured with the M-Fast-FSSP for three different $m$-values (# is number of counts), and with the Fast-FSSP.](image-url)
Figure 5.20: Profile from September 15, 2002. a: effective radius measured with the Fast-FSSP, the M-Fast-FSSP, and the PVM. b: Width of the size distribution measured with the M-Fast-FSSP and the Fast-FSSP.

count number of 1000 for accumulating a statistically meaningful size distribution. When processing the measurements with \( m = 0.8 \) (thin solid line), there are not sufficient counts, and the distribution is corrupted by random fluctuations. If one needs to use \( m = 0.8 \), one can either choose a longer accumulation interval (10 seconds for Figure 5.19) or combine size bins to have a larger count number per bin.

In Figure 5.19, the instrumental broadening by the M-Fast-FSSP is rather weak because near cloud base, there are only small drops which do not contribute much to instrumental broadening. This explanation can be given due to the similar behavior of the instrument for small glass beads (section 5.3.8). The profile of the drop effective radius and of the width of the size distribution, shown in Figure 5.20, confirms this effect: At cloud base with small drop sizes, the different \( m \)-values for the M-Fast-FSSP and the Fast-FSSP give the same result for the width. In contrast, a large difference is observed at cloud top. For \( m = 1.0 \) and for the Fast-FSSP, 5 \( \mu m \) are measured, while \( m = m_{\text{min}} \) gives 2.5 \( \mu m \). The extrapolated width is even decreased to 2 \( \mu m \). While the width is increasing with height above cloud base for the Fast-FSSP measurements and for \( m = 1.0 \), the extrapolated width from the M-Fast-FSSP measurements is almost constant above 1550 m. This is a substantial difference. A constant width above cloud base as predicted by condensational drop growth models was only rarely observed in the past. The effective radius measured with the M-Fast-FSSP (full circles for \( m = 1.0 \), other \( m \)-values not shown) is consistent within the range of \( m \)-values and with the Fast-FSSP measurements (open circles). The PVM (small full circles) underestimates the drop size for large drops. This has been explained by the decreasing sensitivity of this instrument towards large drops (Wendisch et al., 2002b).
Figure 5.21: M-Fast-FSSP concentration measurements for the whole flight of September 15, 2002: $m = 1.15$, and $m = 0.95$, plotted as a function of $m = 1.20$.

In Figure 5.21, the concentrations derived from the M-Fast-FSSP for different $m$-values are compared, using data from the whole flight. No coincidence correction was applied. While data for $m = 1.15$ (circles) correspond very well with the reference $m = 1.20$, the measurements for $m = 0.95$ are higher, especially for large concentrations. This tendency is confirmed when fitting lines to the scatter plot for all $m$-values which were used. The slopes of these fits are shown in Table 5.3. For $m = 0.9$, the measured concentration is overall 32% higher than for $m = 1.2$, while the deviation is only 1% for $m = 1.15$. The tendency is probably caused by coincidences. For low $m$-values, the concentration is not underestimated as much as for higher $m$-values. Since the coincidence corrections which were suggested by e.g. Brenguier and Amodei (1988) involve the activity of the probe which is defined using the total drop duration (formula 5.9), no dependency on $m$ is provided. The theory of coincidence corrections therefore needs to be modified. Part of it has been introduced in section 5.3.7.

For the LWC measurements, there is no such clear trend. In the same way as for the concentration measurements, the LWC measured for different $m$-values has been plotted to a reference of $m = 1.20$ for the whole flight, and lines have been fitted (slopes in Table 5.4). Hence, while the concentration measurements are highly sensitive to changes in the sampling volume, the LWC measurements are rather indifferent. This is because the coincidences cause mainly the concentration of small drops to be underestimated, which contribute only little to the LWC.

<table>
<thead>
<tr>
<th>$m$</th>
<th>0.90</th>
<th>0.95</th>
<th>1.00</th>
<th>1.05</th>
<th>1.10</th>
<th>1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope</td>
<td>1.32</td>
<td>1.17</td>
<td>1.06</td>
<td>1.04</td>
<td>1.02</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 5.3: Slopes of the scatterplots vs. $m = 1.20$ for different $m$ in Figure 5.21.
Table 5.4: Slopes of the scatterplots of LWC for the M-Fast-FSSP \((m = 0.9 \ldots m = 1.15)\), the Fast-FSSP, the PVM and the Nevzorov probe vs. the M-Fast-FSSP for \(m = 1.20\).

Moreover, the \(m = 1.20\) measurements have been compared to the Fast-FSSP measurements, the PVM, and the Nevzorov probe. The Nevzorov probe measures 10% higher \(LWC\) values, the other instruments agree within 7%. The Nevzorov probe measurements have not yet been systematically studied. One reason for the high \(LWC\) measurements may be the presence of large drops. Their concentration might be underestimated by the Fast-FSSPs.

5.4.2 Balloon Measurements

Figure 5.22 shows a profile measurement (descent) with the balloon on May 22, 2003. The \(LWC\) profile (a) shows a distinct minimum at an altitude of about 640 m which marks the top of the boundary layer. The M-Fast-FSSP shows slightly lower values for \(LWC\) than the PVM, except at high altitudes and thus high mean drop diameters. The dropping PVM

![Graphs showing altitude profiles and concentration profiles with different markers and lines for M-Fast-FSSP, Fast-FSSP, and PVM.]

Figure 5.22: Measured altitude profiles. a: \(LWC\) (solid line: PVM; closed circles: M-Fast-FSSP, \(m = 1.0\), \(d < 26 \mu m\) only; open circles: \(m = 1.0\), all channels; dotted line: adiabatic profile). b: drop concentration M-Fast-FSSP, \(m = 1.0\). c: Effective radius M-Fast-FSSP, \(m = 1.0\). d: Width from M-Fast-FSSP - crosses: \(m = 1.5\), closed circle: \(m = 1.0\), triangle: \(m = 0.85\), crossed circle: extrapolated width. (Figure adopted from Schmidt et al., 2004)
sensitivity for large drop diameters is accounted for by summing up the M-Fast-FSSP measurements up to 26 µm only, which then gives a good agreement between both instruments. This means that the PVM does not measure the larger tail of the drop size distribution. The LWC profiles is far below an adiabatic profile (dotted line).

Below the level of 640 m, both LWC and drop concentration show higher fluctuations than in the upper cloud layer. The mean drop diameter (Figure 5.22c) increases almost linearly with height and seems to be insensitive to the position of the boundary layer, while the concentration (b) shows a clear jump.

The discontinuity is also visible in Figure 5.22d which shows the profile of the width σ of the drop size distribution. In this case, σ increases with height above cloud base up to about 530 m. There is only a small difference between the m = 1.0 measurements and σ obtained from m = m₀ = 0.85, and the extrapolation. From this level up to the altitude where LWC reaches its second maximum, the width of the drop size distribution decreases with height. The decrease is similar for m = 1.0 and m = 0.85, but more significant for the extrapolation. At cloud top, an increase of the width obtained from both methods is observed.

Figure 5.23 shows the size distributions for Figure 5.22 for two different levels: below 640 m at 530 m (first maximum of the LWC), and above, near the cloud top (970 m). Since the count number for all distributions is considerably below 1000, a smoothing over five size bins was applied to increase the statistical significance of the size distributions. The observed peaks are related to statistical fluctuations. For m = 0.85 (solid lines), the width of the size distribution measured at the two heights is approximately the same (≈ 4 µm), while for m = 1.5, the width measured at 970 m is somewhat larger. In this cloud case, minimizing the instrumental broadening does not cause a radical change of the vertical profile. However, for the upper cloud part, the extrapolated widths are by far lower than obtained without extrapolation; in the lower part, applying the principle does not show a considerable effect.
Chapter 6

Reproducing 3D Cloud Fields

6.1 Problem Description

When studying the effects of cloud inhomogeneities on radiative parameters, the major problem is to provide three-dimensional cloud fields as input for radiative transfer calculations. In-situ microphysical observations by aircraft, balloon, or zeppelin provide data along the trajectory of the measuring platform. Though this method is very effective for detailed microphysical cloud characterization, it is difficult to estimate the three-dimensional cloud structure from these one-dimensional data. Remote-sensing techniques such as satellites, radars or microwave radiometers allow to scan the cloud structure within an extended region and provide two- or three-dimensional snapshots of the cloud situation. However, when retrieving microphysical quantities from remote measurements, large errors are introduced. For example, satellite measurements provide information about the cloud type, structure, and cover, but the retrievals of the LWP are not reliable enough for radiative transfer calculations. Likewise, Radar measurements of LWC profiles and of the LWP are still not sufficiently accurate to be used directly as modeling input. Ideally, in-situ microphysical measurements for detailed microphysical data, and satellite and radar measurements for a qualitative characterization of the structure of the three-dimensional cloud field are combined. Three different types of algorithms for generating three-dimensional cloud fields can be distinguished:

1) **Direct methods** are applied if only data collected by aircraft are available. The one-dimensional measurements are directly mapped onto a three-dimensional grid, and extended to three dimensions using some basic assumptions.

Los and Duynkerke (2000) show how to produce horizontally and vertically variable fields of optical parameters from aircraft measurements of the LWC in stratocumulus clouds. The cloud top height was set constant, which was justified by measurements with a downward-looking lidar. For the vertical structure of the cloud layer, an adiabatic profile was assumed. The cloud base height was calculated from the LWC measurements of a horizontal in-cloud flight leg using the vertical gradient of the LWC. This gradient was calculated from standard meteorological measurements. Across flight direction, no variation of cloud parameters was implemented. This field was then used for radiative transfer calculations.

Räisänen et al. (2003) present a scheme which explicitly takes into account the horizontal variability of the drop effective radius. They used microphysical measurements from horizon-
tal flight legs through stratiform clouds. A constant cloud top and base height were assumed. In the vertical, the LWC and the effective radius were either assumed to be constant or to follow adiabatic profiles. No horizontal variation of cloud properties was considered across the flight direction.

Partly unjustified assumptions are made by both approaches, in particular about cloud top and base structure. A constant cloud top or base height is usually not observed for stratus layers. Wood and Taylor (2001) explain the observed variability of the LWP time series measured in stratocumulus clouds by a varying cloud base. Radar and ceilometer measurements by e.g. Crewell et al. (2004) show that there is also a considerable cloud top height variability. Since the radiative transfer is very sensitive to the cloud top structure, modeling a flat cloud surface is not acceptable. Assuming adiabatic or even constant LWC profiles for extending horizontal measurements to the vertical dimension may also lead to unrealistic cloud fields.

2) Physical methods are used to fill the gaps of information between one-dimensional aircraft measurements and the three-dimensional grid based on atmospheric processes.

With large eddy simulations (LES), the evolution of clouds can be modeled using a set of detailed input parameters. Chosson and Brenguier (2004) present an approach where airborne measurements of cloud microphysical and meteorological parameters are used to initialize a LES model. This approach requires no assumptions about the cloud top or base structure and about the internal variability. The horizontal cloud heterogeneity is obtained from the mixing processes which are implemented in the model. However, since this is not the only source for cloud inhomogeneities, the modeled horizontal cloud structure can deviate considerably from the measurements even if the mean profiles of bulk microphysical parameters are consistent. Especially for rapidly changing meteorological situations and cloud types, the method cannot be applied.

3) Surrogate methods generate cloud fields whose statistical properties are similar to one- or two-dimensional measurements. An overview about surrogate time series is given by Schreiber and Schmitz (2000). The most recent algorithm was developed by Venema et al. (2004) to assimilate data from the instruments which were used during the BBC-2001 and BBC-2003 experiments. Thereby both one-point statistics (e.g. probability distributions of cloud parameters) and two-point statistics (measured structure of the field, e.g. by power spectrum) are considered. The advantage of this algorithm is that a statistical description of the cloud field from a variety of instruments observing different or similar parameters can be combined. The surrogate approach is currently the only way to handle complex cloud scenarios, provided that the respective statistical parameters are measured with sufficient precision. Direct and physical methods cannot be applied to reproduce complex cloud fields as encountered during the BBC-2001 and BBC-2003 campaign.

In contrast to the BBC experiments, instrumentation for characterizing the macroscopic structure of the cloud fields such as radars was missing during INSPECTRO, and the only data source were aircraft measurements of cloud microphysics. This work is aimed at reproducing a stable stratus cloud layer which was encountered on September 14, 2002, characterized by several profile measurements and by one in-cloud horizontal leg (section 4.2.1). The generated cloud fields serve as input parameter for three-dimensional radiative transfer calculations.
In the following section, several methods are discussed for deriving cloud statistics and structure from the aircraft measurements, such that they can be used by the cloud generating schemes (section 6.3).

6.2 Methods for Characterizing 3D Cloud Fields

6.2.1 Profiles

As a first approach, profiles of the LWC and the layer cloudiness are examined. The layer cloudiness or cloud fraction \( c_h \) is derived from the measured time series of the LWC along the flight track by counting the cloudy data points per cloud layer and by normalizing by the total number of data points measured within each layer. Thereby, the definition for 'cloudy' was set to

\[
LWC \geq 0.05 \text{ g m}^{-3}. \quad (6.1)
\]

If no cloud is present within \( h \) and \( h + \Delta h \), where \( \Delta h \) is the layer thickness, \( c_h = 0 \). If the layer is entirely occupied by clouds, \( c_h = 1 \). Figure 6.1a-c shows three different profiles of the LWC (lines with errorbars) and of \( c_h \) (columns). The error bars show the standard deviation \( \sigma_{i,h} \) of the LWC measurements along the flight leg \( i \) between \( h \) and \( h + \Delta h \). It reflects both vertical and horizontal variability because the aircraft flies along a slant path. Vertical and horizontal parts of the variability cannot be separated by aircraft measurements. For the stratus layer which was measured in this case, one would expect a monotonically increasing LWC with height above cloud base (adiabatic model). In Figure 4.11, it was shown that the profiles are nearly adiabatic. The deviations from this behavior which is observed at e.g. 650 m and 750 m in Figure 6.1b are probably due to horizontal LWC variability when the aircraft crosses the interface between two cloud columns with different base height. Cloud fractions between 0 and 1 were caused by cloud top and base height variability. While the aircraft was measuring within a layer close to cloud top or base, it was partly in the cloud and partly outside along its path.

In Figure 6.1d, the profiles from Figure 6.1a-c are averaged. The local standard deviations \( \sigma_{i,h} \) which are found for the individual profiles are combined by \( \sigma = \sqrt{\sum \sigma_{i,h}^2} \) (dashed line). The global standard deviation \( \sigma_g \) (dotted line) relates to the deviation of the three individual profiles \( LWC_{h,i} \) with respect to the averaged profile \( \langle LWC \rangle_h \):

\[
\sigma_{g,h} = \sqrt{\frac{1}{2} \sum_{i=1}^{3} (LWC_{h,i} - \langle LWC \rangle_h)^2}. \quad (6.2)
\]

The error bars in Figure 6.1d comprise the combined global and local variability \( \sqrt{\sigma_{i,h}^2 + \sigma_g^2} \). The ratio between \( \sigma_g \) and \( \sigma_i \) can be used as a rough qualitative measure for the deviation of the cloud from a uniform layer, and hence for its inhomogeneity. If \( \sigma_g/\sigma_i \ll 1 \), the individual profiles do not differ very much with respect to the internal variability within each profile. Therefore, the cloud can be reproduced by extending the averaged profile horizontally all over the grid. However, for the measured cloud layer, \( \sigma_g/\sigma_i \approx 1 \). This suggests a three-dimensional approach for cloud reproduction. For \( \sigma_g/\sigma_i \gg 1 \), large differences occur between
Figure 6.1: a–c: Three individual profile measurements of the LWC (line with errorbars, indicating the variability $\sigma_i$, within the layer along flight leg $i$), and of the layer cloud fraction $c_h$ (columns). d: averaged profiles and local variability $\sigma_l$ (thin line) from a–c, and global variability $\sigma_g$ (dotted line) indicating the deviation of the three profiles from the average profile. The error bars of the LWC profile comprise $\sigma_l$ and $\sigma_g$.

the profiles, and the suggested stratiform characterization of the cloud layer might fail. Both $\sigma_l$ and $\sigma_g$ are biased by cloud gaps: For $c_h < 1$, enhanced values of these measures of cloud variability are derived for layer $h$. This is seen at cloud top in Figure 6.1. The LWC values in the individual layers are not Gauss distributed. Thus, the description of the cloud field in terms of $\sigma_l$ and $\sigma_g$ gives merely a rough estimate of the data quality. In the next section, the probability density functions will therefore be introduced to characterize the measurements.

6.2.2 Probability Density Functions

The averaged LWC profile can only be used for overcast cloud layers ($c_h = 1$) for homogeneous conditions ($\sigma_g / \sigma_l \ll 1$). If $c_h < 1$, as for broken cloud fields, the mean $\langle LWC \rangle_h$ within the cloud and the cloud gaps are mixed, and the averaged profile is characterized by the effective $\langle LWC \rangle_h^* = c_h \langle LWC \rangle_h$ for the layer $h$. Sharp interfaces are removed when averaging profiles with different cloud top or base height. For example, the sharp cloud top which is seen in Figure 6.1a is not preserved in Figure 6.1d. Since the radiative transfer is very sensitive to cloud top structure, a flattened LWC profile may cause errors when using the cloud for radiative transfer calculations. Furthermore, the standard deviation does not
Figure 6.2: Two-dimensional PDF of the $LWC$ and $R_{\text{eff}}$ for three different altitudes. Dark pixels indicate a high probability. The PDF are normalized to unity for each level separately.

adequately describe the probability distribution of the $LWC$ values within a layer. The probability density functions

$$p_h(LWC; R_{\text{eff}})$$

(6.3)

are obtained from the measurements by binning the measured values of $LWC$ and $R_{\text{eff}}$ into classes for each height level. Subsequently, the histograms are normalized for each level separately. The mean $LWC$ value

$$\langle LWC \rangle_h = \sum_i LWC_i \sum_j p_h(LWC_i; R_{\text{eff},j})$$

(6.4)

is based on the in-cloud measurements only, and is higher than the effective mean $LWC$ value from section 6.2.1 if $c_h < 1$. The microphysical characterization $p_h(LWC; R_{\text{eff}})$ is thus separated from the macrophysical parameter $c_h$ which was mixed in the effective mean $LWC$. Moreover, the effective radius is included in this PDF. The advantage of a two-dimensional PDF is that both microphysical parameters are coupled. When using two independent PDFs, the correlation between $LWC$ and $R_{\text{eff}}$ would be lost. This is illustrated by Figure 6.2 where the PDFs obtained from the profiles taken on September 14, 2002, are plotted at three different altitudes (700, 800, and 900 m). Dark pixels correspond to a high probability. The correlation between the $LWC$ and $R_{\text{eff}}$ is not linear. Apparently, neither the $LWC$ nor $R_{\text{eff}}$ are Gauss distributed.

Figure 6.3 shows the one-dimensional PDF $p_h(LWC) = \sum_j p_h(LWC; R_{\text{eff},j})$ for three different altitudes (a: 1100 m, b: 900 m and 1120 m). Vertical arrows are plotted at the mean $LWC$ values, and the horizontal error bars correspond to the total standard deviation $\sqrt{\sigma_g^2 + \sigma_l^2}$. The in-layer variability of the $LWC$ is clearly not sufficiently reflected by this standard deviation. In the PDF, there are several maxima which can be traced back to individual profiles with different cloud base and top height.

An accurate measure for the statistical significance of $p_h$ and $c_h$ cannot be given because the aircraft does not sample the whole grid, and the statistical properties are only estimated on the base of a limited number of transects through the cloud layer.
Figure 6.3: One-dimensional PDF $p_h(LWC)$ for three different heights (a: 1100 m, b: 900 m and 1120 m). The horizontal error bar corresponds to the total standard deviation $\sqrt{\sigma_t^2 + \sigma_q^2}$. The mean $LWC$ values are indicated by vertical arrows.

6.2.3 Power Spectra

The quantities $p_h$ and $c_h$ contain the one-point statistical properties of the cloud measurements for each layer. However, there is no information about the structure within this layer. Therefore, a second-order or two-point statistical description of the cloud layer is required. This is provided by using the power spectrum of the series $LWC(t)$ which is calculated from the discrete Fourier transform

$$\overline{LWC}(f_k) = \sum_{n=0}^{K-1} LWC(t_n) e^{2\pi if_k t_n} \Delta t. \quad (6.5)$$

Thereby, $t_n=[t_0 \ldots t_{K-1}]$ denote either a time or position in space, and $\Delta t$ the respective interval. The corresponding frequencies (wave numbers) are $f_k = k/K \Delta t$, $k=[-K/2 \ldots K/2]$. $K$ is the number of data points in the series. The highest frequency of the Fourier transform $f_{K/2}$ is half of the sampling frequency $f_s = 1/\Delta t$, due to the Nyquist theorem.

For simplicity, time series are analyzed here, and the transition between time and position is provided by the true air speed ($TAS$) or by the speed over ground. In this case, $TAS$ was used because in this way, the cloud field is analyzed relative to the mean velocity at which the cloud field moves over ground.

The variance of the time series is obtained by summing up the squared amplitude of the Fourier transform over all frequencies. This is an alternative way to determine $\sigma_q^2$. The two-sided power spectrum is the squared amplitude of the Fourier transform. The interpretation of this function is the distribution of the variance over the single eddy sizes (frequencies) of a
Figure 6.4: a: Power spectra of the LWC measured with the Fast-FSSP during the horizontal in-cloud leg on September 14, 2002 (noisy solid line up to 0.5 Hz) and the same binned into log-equidistant steps (line with circles). Above 1 Hz, white noise flattens the spectrum, which is otherwise consistent with Kolmogorov’s -5/3 law. The PVM measurements, in contrast, follow this scaling up to 10 Hz and higher (line with squares). b: Power spectra of the concentration measured with the Fast-FSSP at 100 Hz (open circles), the same applying a 5-point-averaging (closed circles) removes some white noise at the high-frequency end, and averaged 500 Hz measurements (closed squares).

For a real-valued function, the two-sided power spectrum is a symmetrical function, and the one-sided power spectrum

$$\text{Pow}_{\text{LWC}}(f_k) = \left| \overline{\text{LWC}(f_k)} \right|^2 + \left| \overline{\text{LWC}(-f_k)} \right|^2 = 2 \left| \overline{\text{LWC}(f_k)} \right|^2$$

(6.6)

is sufficient to characterize the series. The power spectra were numerically calculated with Fast Fourier Transform (FFT, see Stull, 1988).

Figure 6.4 shows the power spectrum of the LWC (a) and of the drop concentration (b) for the horizontal leg which was flown within the cloud layer on September 14, 2002 (section 4.2.1). The LWC is measured with the PVM and with the Fast-FSSP. For low frequencies, measurements of both instruments are consistent with Kolmogorov’s scaling law $f^{-5/3}$. The raw Fast-FSSP measurements (noisy solid line) are shown for an accumulation time $\Delta t = 1$ s, i.e. $f_s = 1$ Hz. Therefore the highest frequency of the power spectrum is 0.5 Hz. For high frequencies, the power spectrum appears very noisy. Therefore, a binning with log-equidistant frequency-intervals was performed to visualize the scaling. The line with open circles shows the binned 20 Hz Fast-FSSP power spectra. For frequencies higher than 0.5 Hz, the power spectrum of the Fast-FSSP measured LWC is flattened which is not observed for the PVM measurements (line with open squares). This difference is caused by the different size of the sampling volumes of the two instruments. For the Fast-FSSP, the sampling volume is small compared to the PVM, and for short accumulation times, the collected drop data are not statistically significant. The measurements are thus biased by Poissonian noise which increases the variance at high frequencies.

This is also observed for the power spectra of Fast-FSSP concentration measurements...
(Figure 6.4b). The line with open circles shows the power spectrum from the raw data which was accumulated at 100 Hz. When applying a 5-point filtering to these data (line with closed circles) the variance offset at high frequencies can be reduced, but not removed, likewise when applying the filtering to 500 Hz sampled data (line with squares). This behavior of the Fast-FSSP power spectra at high frequencies is fully understood from the theoretical background of the instrument. As consequence, very short range studies of cloud structure can only be accessed by applying a filter which accounts for the Poissonian nature of the counting process. Pawlowska et al. (1997) and Pinsky and Khain (2001, 2003) developed nonlinear filter techniques to access very small scales.

![Power spectra graph](image)

Figure 6.5: Power spectra of the downward (solid line) and upward irradiance (dotted line), measured for $\lambda = 500$ nm for the same leg as for Figure 6.4 (a), and for a flight leg above clouds (b). Within clouds, the power spectra scale as the microphysical time series with $f^{-5/3}$ up to scales of about 5 km. For smaller scales, a lower slope is found. Above the cloud layer, the downward irradiance variance is lower than the upward measurements, and no visible scale break is observed for the upward irradiance.

For the same leg as in Figure 6.4, power spectra of the up- and downward irradiance at a wavelength of 500 nm (sampling frequency 0.8 Hz) are shown in Figure 6.5a. Within the cloud layer, the power spectra are nearly the same for the up- and the downlooking sensor. For low frequencies, the irradiance scales with the $f^{-5/3}$ law which can be expected from the microphysical measurements. At about 0.07 Hz (corresponds to about 1 km, with $TAS \approx 70$ m s$^{-1}$), a scale break is found, and for high frequencies, a power law of $f^{-3.28}$ is observed. The physical interpretation of this phenomenon is that for scales above 1 km, the structure of the irradiance field follows the microphysical LWC. For smaller scales, variability is lost due to horizontal photon transport. At 0.009 Hz, there is an enhanced value of the power spectrum within the cloud layer. This corresponds to about 7 km which is in the same range as the main spatial scale which could be estimated from the time series of the in-cloud LWC and irradiance measurements (Figure 4.8).

For the irradiance measurements above cloud (Figure 6.4b), no clear scale break is observed. The downlooking sensor detects the variability of the cloud layer below. Fitting a line to the power spectrum in the range between 0.02 and 0.4 Hz yields a flatter slope
than within the cloud: A scaling exponent of 2.6 is found. The time series of the downward irradiance above the cloud layer is rather smooth. Therefore a power spectrum does not make sense.

### 6.2.4 Leap Probability Function

Besides power spectra, there is a variety of other measures for the structure. The main virtue of power spectra is the easy detection of scaling laws from the time series. However, spatial scales occurring as maxima at certain frequencies are not easily detected. For this purpose, autocorrelation functions are more suitable. A further tool are structure functions. For the LWC, the structure function of order is defined as the statistical moment of the absolute value of jumps in the time series LWC(t):

$$
\phi^q(\Delta t) = \langle |LWC(t + \Delta t) - LWC(t)|^q \rangle .
$$

Other measures for the variability of the time series such as the singularity measure are described in Marshak et al. (1997). The application of the structure functions to analyze the horizontal cloud structure is published in Davis et al. (1999). Malinowski et al. (1994) describe a cluster analysis technique for examining the turbulent cloud structure on the basis of FSSP or Fast-FSSP measurements.

Here, a new measure for quantifying the probability of LWC jumps is introduced. The LWC leap probability function \( \Lambda(\Delta LWC; \Delta r) \) is defined as the probability for a jump \( \Delta LWC \) to occur over a distance \( \Delta r \) in the cloud. It is calculated from the LWC time series by converting \( \Delta t \) to \( \Delta r \) using the TAS, and by counting the frequency of the jump

$$
\Delta LWC(\Delta r) \equiv |LWC(r + \Delta r) - LWC(r)|
$$

for each \( \Delta r \). A normalization is applied for each \( \Delta r \) separately such that

$$
\sum_i \Lambda(\Delta LWC_i; \Delta r) = 1.
$$

![Figure 6.6: Leap probability for three different LWC jump intervals as a function of the distance \( \Delta r \). Two typical scales are visualized by local maxima or minima of the curves: 3.5, and 6.5 km. At 2 km, most jumps from minimum to maximum LWC occur.](image-url)
In Figure 6.6, the leap probability function is plotted for $\Delta LWC < 0.05$ g m$^{-3}$ (solid line), $\Delta LWC = [0.05, 0.10]$ g m$^{-3}$ (dashed line), and $\Delta LWC = [0.10, 0.15]$ g m$^{-3}$ (dotted line). At $\Delta r = 0$, the only possible jump is clearly $\Delta LWC = 0$, $\Lambda(\Delta LWC, 0) = 1$. At $\Delta r = 2$ km (left arrow), there is a local minimum for the probability of $\Delta LWC < 0.05$ g m$^{-3}$. The other probabilities achieve a local maximum. The interpretation of the local minimum of the solid line is that at this distance, most of the minimum - maximum couples are found in the series of the LWC. The opposite is observed for a distance of 3.5 km, which can be interpreted as the mean period of the series where most of the maximum - maximum or minimum - minimum couples occur in the LWC series. Another local maximum is found for $\Delta r \approx 6.5$ km which corresponds to the observed mean period of the irradiance in Figure 4.8.

Although the typical scales can easily be identified by looking at the original time series in Figure 4.8, the power spectrum does not clearly show them, whereas the method with leap probabilities extracts typical structures from the data.

### 6.3 3D Cloud Reproduction

In this section, some of the microphysical and macroscopical statistical properties which were presented in the previous section for the overcast stratus layer of September 14, 2002, are used to reproduce three simple model cloud layers. The three algorithms are not aimed at reproducing the physically correct cloud structure. This cannot be achieved with such sparse input data. Instead, the intention is to compare the statistical properties of the measured and of the modeled radiation, using the three different clouds as input parameter for radiative transfer modeling.

#### 6.3.1 Algorithms

1) **HOM_CLOUD:** The homogeneous cloud layer (hom_cloud) is generated as one-dimensional reference from the mean profile of the LWC (section 6.2.1) and of the effective drop radius by assigning the averaged profile measurements to all columns of a grid with 33x57 pixels with 0.5 km box length. Each column contains 90 height levels (see Table 6.1). Within the cloud layer, the vertical spacing is 20 m.

2) **PDF_CLOUD:** The second cloud type (PDF cloud) implements the two-dimensional probability density functions of the LWC and of $R_{\text{eff}}$. For each box, the couple of the LWC

<table>
<thead>
<tr>
<th>height range [m]</th>
<th>vertical spacing [m]</th>
<th>number of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-400</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>400-1100</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>1100-3000</td>
<td>100</td>
<td>19</td>
</tr>
<tr>
<td>3000-25000</td>
<td>1000</td>
<td>22</td>
</tr>
<tr>
<td>25000-50000</td>
<td>2500</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6.1: Vertical spacing of the cloud columns
and $R_{\text{eff}}$ is picked by using two random number generators reproducing the PDF which was measured for the respective height level. For the levels with a cloud fraction less than unity, only a part of the boxes corresponding to $c_h$ were filled.

No preferential filling order of the boxes is implemented, the levels are filled one after another. The horizontal grid points are chosen by a third random number generator. Neither horizontal nor vertical correlations are considered by this scheme. Only one-point microphysical and macrophysical statistical properties are reproduced. Therefore, the PDF.CLOUD is used as reference for using one-point statistics only, with decoupled boxes.

3) **SHIFT.CLOUD:** For the third cloud type, one-point- as well as two-point statistical information are implemented. The columns are filled with the mean profile of the $LWC$ and of $R_{\text{eff}}$ which is obtained from $p_h(LWC; R_{\text{eff}})$. In contrast to the HOM.CLOUD where for $c_h < 1$, the effective $LWC$ is used, this supplied a more realistic mean profile. In the horizontal, the grid is filled line after line with the mean $LWC$ and $R_{\text{eff}}$ profile which is shifted upward or downward such that it fits the $LWC$ that was measured along the in-cloud leg and averaged over the box side length. In this way, no variations of the $LWC$ profile are implemented along the line while the cloud top and base variability across the lines is determined by using the horizontal microphysical in-cloud measurements directly. The power spectrum or the structure function are not required. The vertical correlations are considered by using the mean profile. However, as stated above, horizontal variations are contained in the vertical profile measurements, and the vertical variability is probably lower than assumed.

6.3.2 Validation

The output of the three algorithms described above was tested by comparing the resulting mean profiles and cloud top and base height probability distributions with the input data.

Figure 6.7a shows all $LWC$ profile measurements with the PVM (crosses) and the mean measured $LWC$ profile (line with squares, cloud top height between 800 and 950 m). For hom.CLOUD (dashed line), exactly the mean measured profile is used for reproducing the cloud. The small deviations from the measurements are due to grid effects.

The solid line shows the reproduced profile for the pdf.CLOUD. In contrast to the hom.CLOUD profile, the mean reproduced $LWC$ values at cloud top are generally higher. This is caused by empty pixels which are generated for layers with $c_h < 1$. The layer average $LWC$ is determined from the occupied boxes only. For hom.CLOUD, all pixels are occupied with the effective $LWC$. For pdf.CLOUD, the occupied boxes are assigned an $LWC$ according to the probability density function of the $LWC$. The shift.CLOUD mean $LWC$ profile (dash-dotted line) is far more spread than the other profiles because the mean measured profile is shifted upward and downward to produce this cloud.

Figure 6.7b shows the cloud top and base heights which were determined from the reproduced cloud fields by counting the highest (lowest) occupied pixels to histograms and by normalizing by the number of horizontal grid points. The hom.CLOUD is bounded by two clearly defined layers at 600 and 1040 m. Below 600 and above 1040 m, the average $LWC$ is below 0.05 g m$^{-3}$ which defines the cloud boundaries. For pdf.CLOUD and shift.CLOUD, the
cloud edges vary considerably. For shift\_cloud, the lowest observed cloud top height is 780 m which does not agree with any of the profile measurements. It is caused by a large height offset, suggested by the horizontal leg data. The cloud top variability of the pdf\_cloud is not as large, and represents exactly the profile measurements.

The horizontal structure is characterized by independent columns with LWP values ranging between 100 and 250 g m\(^{-2}\). For hom\_cloud, all columns have a LWP of 181 g m\(^{-2}\). For shift\_cloud, the same LWP is obtained for all columns because the same profiles are used. The power spectrum along an arbitrary line through the pdf\_cloud shows no frequency dependence. This is what is expected because no horizontal structure is imposed on pdf\_cloud. For the shift\_cloud, the power spectrum along the lines is zero, because no variability in this direction was implemented. Across the lines, roughly the same power spectrum as for the measurements is reproduced.

Summarizing, the hom\_cloud represents the mean measured LWC profile, and a cloudiness below unity results in a decreased effective LWC for all pixels. The same profile is used all over the grid. In contrast, the pixels of the pdf\_cloud are filled using \( p_h(LWC; R_{\text{eff}}) \) and \( c_h \). Neither horizontal nor vertical structure is imposed on the cloud. The shift\_cloud is a straightforward realization of the horizontal and vertical structure found in the measurements. The measured power spectrum is recovered in the reproduced cloud. However, the mean measured LWC profile is not conserved.
Chapter 7

Radiative Transfer Calculations

7.1 Model Selection

For solving the radiative transfer equations (RTE), three-dimensional modeling of the radiation field is crucial to fully account for the effects of cloud inhomogeneities of the reproduced cases from September 14, 2002. Currently, there are mainly the following types of three-dimensional radiative transfer models (RTM) available:

a) The independent column approximation (ICA) was developed by Cahalan et al. (1994) to extend the plane parallel (PP) model to three dimensions and thus to reduce the overestimation of the cloud albedo by the PP model (albedo bias: Barker, 1992, Hignett and Taylor, 1996). With this approach, the three-dimensional cloud structure is approximated by independent cloud columns for which one-dimensional RTM can be applied. However, horizontal photon transport between the columns is not considered in the ICA.

b) Monte-Carlo (MC) solvers model the radiation field by tracing individual photons on their way through the three-dimensional atmosphere. One of the advantages of this type of model with respect to ICA is that the horizontal photon transport is not neglected. The number of photons which are used for modeling determine the accuracy of the results. With respect to one-dimensional RTM and to ICA models, MC models require more computational resources.

c) With the spherical harmonics discrete ordinate method (SHDOM, Evans, 1998), the RTE can be solved along arbitrary directions by expanding the radiation field to spherical harmonics (Evans, 1998). This method is much faster than MC methods, but inappropriate for modeling domain averaged radiation quantities for large fields because of the high demand of working space.

For domain-averaged irradiances and for modeling the albedo of inhomogeneous clouds, horizontal photon transport can be neglected: Los and Duynkerke (2001) showed that the differences between ICA and the MC modeled stratocumulus albedo is below the statistical uncertainties of the MC result. However, the local properties of the radiative field are highly sensitive to horizontal photon transport. Radiative smoothing (e.g., Marshak et al., 1995) is not reproduced by the ICA. In contrast, when using MC models, radiative smoothing can be reproduced. By horizontal photon transport, the mean free photon path length within clouds may be increased, which is one possible reason for an enhanced cloud layer absorption with respect to ICA results. The MC modeled macroscopic properties of the radiation field
can also differ from ICA results. In particular, the photon density below cloud holes may be enhanced with respect to ICA. Horizontal photon transport may have a considerable influence on the absorptance estimated from formula (2.14). This was demonstrated by Gimeno et al. (2003) for a measurement case from BBC-2001.

In this work, the Monte carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres (MYSTIC, Mayer, 1999; Kylling et al., 2000) was used. This MC model was validated during the I3RC (Intercomparison of 3D Radiation Codes) campain (Mayer, 1999 and 2000). It is a forward photon tracing method which considers the interaction of the photons with scatterers and the ground without unphysical assumptions and conserves energy. It can be considered as exact solution of the RTE for a sufficient number of photons within the statistical counting uncertainty of MC models.

MYSTIC is embedded in the freely available libRadtran model package (LRM, Mayer et al., 1997, http://www.libradtran.org). This package hosts several RTE solvers and includes a data base of atmospheric parameters such as optical properties, profiles of model atmospheres. The package has been validated by comparing the model output with other models (van Weele et al., 2000) and with measurements (Mayer et al., 1997). All gases within the wavelength range of the albedometer (see section 3.2.2) are considered. Wendisch and Mayer (2003) used the package to calculate spectral irradiances which were measured by the albedometer under cloudless conditions (one-dimensional modeling).

7.2 Description of MYSTIC

Within the LRM package, MYSTIC is called from the base program uvspec which supplies it with the necessary input data. Since the computational effort is much larger for three-dimensional modeling, only one wavelength (500 nm, near the maximum of the solar spectrum) within the range of the albedometer has been chosen so far for model-measurement comparison. The measurements on September 14, 2002, were conducted in clean maritime conditions. Since the model studies were performed for an overcast cloud case, the aerosol optical thickness is negligible compared to the cloud optical thickness. Therefore, for this study, the effect of aerosols was not considered.

Besides the three-dimensional cloud file containing the LWC and $R_{\text{eff}}$ for each grid point, the following input parameters are required for MYSTIC:

- A file with the vertical profile of atmospheric parameters. For this study, the midlatitude summer standard atmosphere which is provided in the LRM data base (Anderson et al., 1986) is used to define the pressure, the temperature, the air density, the density of $O_3$, $O_2$, $CO_2$, $NO_2$, and of water from the maximum flight height up to 50 km. From ground to the maximum flight height, the aircraft measurements of temperature, relative humidity, and pressure were used, and the respective densities were rescaled accordingly. Between 3 and 4 km, the values were interpolated between the standard atmosphere and the correct aircraft measurements to provide a smooth transition.

- The solar zenith angle was set to 55° for all calculations, which corresponds to the position of the sun at the beginning of the flight.
• The extraterrestrial flux was taken from Kurudz (1992), contained in the LRM database averaged over 0.1 nm intervals.

• The surface albedo was set 0.037, corresponding to Bowker et al. (1985), for grass at 500 nm. This value is near that found by Webb et al. (2004) for the specific measurement area. For overcast clouds, the surface albedo has no significant impact on the upward irradiance within and above the cloud layer.

• The number of photons which are used determines the statistical significance of the results. It was set between 1,000,000 and 10,000,000, depending on the application.

From the microphysical parameters, the optical parameters are derived by a lookup-table defining the moments of the phase function. This table was precalculated for 500 nm using the program clndpnp from the SHDOM distribution\(^1\). This program generates the phase function from an input file containing LWC and \(R_{\text{eff}}\). The index of refraction for water is used for the specified wavelength. The extinction, single scattering albedo, and the phase functions are calculated by assuming a gamma drop size distribution. The model produces the domain averaged irradiances and actinic fluxes at the specified wavelength for all specified height levels. The three-dimensional output is written in separate files.

\(^1\)http://mit.colorado.edu/~evans/shdom.html
Chapter 8

Radiation Measurements Versus Calculations

In this chapter, measured up- and downward irradiances are compared with the 3D radiative transfer simulations for the three model clouds from chapter 6. Although an overcast situation was encountered on September 14, 2002, the radiation measurements show a high variability (section 8.1). This justifies the comparison strategy (section 8.2). Finally, measurements of down- and upward irradiance below and above the cloud layer (section 8.3), and the measured and simulated layer properties (section 8.4) are compared.

8.1 Variability of Radiation Data

Both the ground-based and the airborne irradiance measurements are highly variable. In contrast, the simulation is made for a fixed time and solar zenith angle. The modeling results refer to the whole grid whereas the radiation measurements are acquired along the flight trajectory.

Therefore, the question arises which parameters can actually be compared. This problem is illustrated by Figure 8.1 which shows all aircraft measurements of the downward irradiance at 500 nm. The dotted lines are the measurements which were converted to SZA=55° (see section 8.2 for a discussion of this conversion). The cloud boundaries are marked by the cloud top and base PDF from the pdf_cloud (dash-dotted lines). Although the mean value of the downward irradiance profile clearly indicates the overcast cloud situation, variations can be seen below as well as within and above the cloud layer. Reasons for the small variation of \( F^+ \) above the cloud layer were discussed in section 4.2.1. Within the cloud, the four profiles differ by the slope and by the internal structure. The different slopes are due to a different extinction and hence LWC profile which is seen by the photons. Different cloud top heights and hence different cloud column integrated LWCs \((LWP)\) cause an offset between different irradiance profiles within the cloud. Moreover, spikes are seen for two of the profiles which are cause by either vertical or horizontal inhomoge-neities in the extinction field.

From the measurements, PDFs of the measured irradiance values for each height level were calculated. They are plotted at 1500 m where the horizontal triangular pattern was flown, for the in-cloud leg at approximately 800 m, and below the cloud layer. The PDFs are normalized to unity. The PDF below the cloud contains the aircraft measurements between
Figure 8.1: All measurements of the downward irradiance at 500 nm (dotted line). Histograms of the downward irradiance are plotted for 1500 m, 800 m, and at ground. The cloud top and base histograms (dash-dotted lines) are plotted for identifying the cloud boundaries.

Ground and 200 m. (Measurements from the ground-based instrument are not shown here.) For the horizontal in-cloud leg at 800 m, a high range of values was measured. This is reflected in the PDF at 800 m. For the height levels where the aircraft did not measure for a long time and thus did not sample a large region, the PDFs do not reflect the full variability of the radiation field. This is a similar problem as described for the PDF of the microphysical parameters and needs to be considered when comparing modeled and measured radiation.

Below the cloud layer, the measured variability is caused by the aircraft moving below the cloud field with varying optical thickness. The highest variations occur near cloud top. When the aircraft flies at this level, it may cross the interface between cloudy and clear air. With respect to the measurements above the cloud level, up to 10% higher irradiance values are measured. This can be explained by reflections from the cloud top when the aircraft is in a cloud gap inbetween two ridges.

Figure 8.2a shows the PDFs of the downward irradiance at 500 nm which was measured by the ground-based instrument (hollow columns) and by the aircraft near ground (filled columns). These histograms are averages over the whole flight time. Figure 8.2b shows the ground-based measurements averaged over each flight hour. Although the averaging interval is large, there are large differences between the individual histograms. The bimodal histogram between 11 and 12 UTC indicates two different regimes of cloud optical thickness.
during this time. Between 10 and 11 UTC, the largest optical thickness was present. Likewise, Figure 8.2c shows three different aircraft legs below clouds. Leg #1 and #4 are very short, therefore, not the whole variability is reflected in the PDFs. The main contribution to the average downward irradiance in Figure 8.2a comes from leg #3a/b. The bimodal structure comes from the two individual profiles #3a and #3b. For averaging, all legs were weighed with their duration.

8.2 Comparison Strategy

For one-dimensional modeling, the mean values of the measured and modeled radiation as well as layer properties are usually compared. For the comparison of three-dimensional radiation fields, the previous section suggests to use PDFs of the measured and simulated radiation field rather than the mean values and the standard deviation. This allows to judge the shape as well as the width of the distributions and to identify the reasons for the differences between measured and modeled results.

The histograms were calculated for a wavelength of 500 nm using all SZA corrected aircraft measurements with valid data (i.e. when the stabilization worked properly). The
SZA correction is justified only if the diffuse radiation can be neglected with respect to direct sun. Strictly, this condition is only valid above the cloud for the downward irradiance. For a perfectly stratiform, i.e. plane-parallel atmosphere, and for a flat surface, the same correction can be applied for both the down- and the upward component because of the symmetry. This may be inappropriate for some special geometries. When looking at the corrected time series of the upward irradiance (not shown), it seems that this component is slightly over-corrected by (4.1), and that the uncorrected time series (Figure 4.8) is nearly independent of the SZA. This compensation effect can be explained by the albedo bias: At high sun, more irradiance is reflected from an inhomogeneous cloud surface. The maximum compensation error which can be made for any of the components, given by the range of the SZA throughout the flight (52-55°), is 7%.¹

The slit-function of the albedometer for 500 nm has not explicitly been considered for this study. Its width is about 2 nm for the albedometer, causing an averaging of the detected spectrum over this range. Within this wavelength range, only minor variations are expected.

In addition to PDFs, modeled and measured layer properties are compared. From the output of the radiative transfer model, the parameters $A$, $T$, and $R$ were derived using (2.14)-(2.16) for each column separately, and histograms of these parameters over the grid were obtained. From these, the mean values were calculated. For the measurements, this method cannot be applied because the aircraft was not measuring above and below the cloud layer simultaneously. Therefore, the measured layer properties were calculated from the averaged irradiance measurements from the flight legs above and below the cloud layer.

### 8.3 Irradiances

#### 8.3.1 Downward Irradiances

![Graphs showing PDFs of downward irradiances](image)

Figure 8.3: Measurement (Aircraft) and simulated downward irradiance at 500 nm below cloud level (0-200 m) for hom_cloud (left), pdf_cloud (center), and shift_cloud (right).

¹Use formula 4.1: $\cos(52°)/\cos(55°) = 1.073 \Rightarrow 7\%$ maximum error.
Figure 8.3 shows the downward irradiance below cloud level (0-200 m altitude). The mean value of the modeled irradiance for all three cloud types is about 0.2 W m⁻² nm⁻¹. This reproduces the mean measured value within the range of measurement uncertainty of the albedometer (0.02 W m⁻² nm⁻¹). The mean values which were measured for the three individual aircraft legs are also close to the simulated value.

For hom_cloud, no variance of the modeled radiation is expected within the horizontal grid because the microphysical cloud parameters are horizontally homogeneous. Therefore, only one bar should appear in the histogram. However, the limited number of photons (10 millions for Figures 8.3 and 8.4) causes a computational variance for the MC model, which is about 0.01 W m⁻² nm⁻¹. This causes the second bar in Figure 8.3.

It is not surprising that the observed variance is not obtained by the pdf_cloud. In this cloud field, no horizontal and vertical correlations were implemented, and merely the one-point statistics of the measured cloud field was reproduced. The structure of the cloud was not considered, and the cloud pixels were randomly occupied. The modeled variability of the pdf_cloud field in the individual layers is canceled out because the layers are decoupled. Therefore the photons effectively see the same average value of microphysical parameters when traveling through the cloud layer, with no respect on the horizontal position.

This is different for the shift_cloud where horizontal as well as vertical correlations were considered. In this case, the measured variability is found in the simulations, and the shapes of the measured and the simulated PDFs are almost similar. However, the measured variance is slightly larger than modeled; in particular, the bar at 0.12 W m⁻² nm⁻¹ is not reproduced by the simulations. These differences are due to the temporal variability of the cloud situation.

### 8.3.2 Upward Irradiances

![PDF](image)

Figure 8.4: Measurement (Aircraft) and simulated upward irradiance at 500 nm above cloud level (1500 m) for hom_cloud (left), pdf_cloud (center), and shift_cloud (right).

In Figure 8.4, upward measured and modeled irradiances above the cloud layer are compared. Overall, the observed variability is larger than below the cloud layer because the
cloud top structure affects the reflected irradiance directly. This high variability is only reproduced by shift_cloud. The mean irradiance is overestimated by the simulation with respect to the measurement (0.85 W m$^{-2}$ nm$^{-1}$). For hom_cloud, (0.89 W m$^{-2}$ nm$^{-1}$), the highest difference to the measurements, though within the range of measurement uncertainty (0.07 W m$^{-2}$ nm$^{-1}$), is observed, which can be explained by the plain-parallel albedo bias. The shape of the PDFs is best reproduced by shift_cloud. These results are biased by about 0.02 W m$^{-2}$ nm$^{-1}$ which is well within the range of measurement uncertainty.

Overall, the simulated results fit best with measurements for the shift_cloud which makes sense because one-point as well as two-point statistics are considered in this cloud type. The pdf_cloud gives the best agreement with the measurements in terms of mean values. However, the variability is not modeled. For the hom_cloud, an albedo bias is observed for the irradiance which is reflected by the cloud layer.

### 8.3.3 Profiles

The mean measured and modeled profile of the up- and downward irradiance is shown in Figure 8.5. The measurements are plotted for only one of the profiles (up- and downward triangles). The modeling results are averaged values for each height level. As shown in the PDFs above and below the cloud layer, the measured irradiances are best reproduced by the modeling results using pdf_cloud. The peak of the measured downward irradiance at

![Graph](image-url)

**Figure 8.5**: Profile of the up- and downward irradiance at 500 nm, measurements for one profile and averaged irradiances modeled with the three cloud types.
cloud top caused by reflections from neighboring cloud surfaces is not simulated for any of the model clouds. The small offset which is observed between the modeled and measured cloud top height is caused by the undulated cloud top structure. For the shown profile, the aircraft entered into the cloud layer below the average cloud top height. The local differences of cloud base and top height make a comparison of PDFs at a fixed height within the cloud layer difficult, because the irradiance has a large gradient.

The one-dimensional modeling results (hom.cld, black solid and dotted line) are slightly lower than the results from pdf.cld. However, the difference to the measurements is not large and would justify to renounce three-dimensional modeling from the point of view of mean values. The shift.cld results (gray solid and dotted line), which gave the best agreement with the measurements above and below the cloud layer both in terms of the mean value, of the standard deviation, and of the shape of the PDF deviates considerably from the measurements within the cloud. This is because the layer thickness is overestimated by shifting the mean LWC profile up- and downward. From the point of view of the profiles, the use of the shift.cld type is therefore not favourable. However, when plotting the standard deviations (not shown) of the modeled and of the measured irradiance (using all measured profiles), only the shift.cld values are consistent with the measurements.

### 8.4 Layer Properties

Finally, as for one-dimensional modeling, the measured and modeled layer properties and mean profile of up- and downward irradiances are compared.

Table 8.1 shows the layer properties absorbance ($A$), transmittance ($T$), and reflectance ($R$) which were calculated from the mean measured and modeled irradiances above and below the cloud layer using formulae (2.14) through (2.16). The standard deviation for the

<table>
<thead>
<tr>
<th>Layer Property [%]</th>
<th>measured</th>
<th>modeled (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>hom.cld pdf.cld shift.cld</td>
</tr>
<tr>
<td>Transmittance</td>
<td>21.7</td>
<td>17.0 18.3 16.4</td>
</tr>
<tr>
<td>Reflectance</td>
<td>74.7</td>
<td>82.4 81.3 81.7</td>
</tr>
<tr>
<td>Absorptance</td>
<td>3.6</td>
<td>0.6   0.4 1.9</td>
</tr>
</tbody>
</table>

Table 8.1: Layer properties $T$, $R$, $A$: measured mean values and standard deviation; mean simulated values for model clouds

measurements was calculated by Gaussian error propagation from the standard deviations of the averaged irradiances above and below cloud.

Overall, the measured reflectance is overestimated by all three model cloud types, at the cost of the transmittance and absorptance. However, the deviations are within the standard deviation of the measurements. The absorptance, which should be increased for significant cloud inhomogeneities, is underestimated by the three model clouds. For shift.cld, the modeled value is substantially higher than for the other cloud types. The high standard deviation of the measured absorptance reflects the high uncertainty of this quantity.

The probability distributions of the modeled layer properties derived from the contributions of the individual columns are shown in Figure 8.6. Moreover, the mean value of
Figure 8.6: Probability distributions of the absorptance $A$ throughout the grid modeled for \texttt{hom\_cloud}, \texttt{pdf\_cloud} and \texttt{shift\_cloud}. Mean values of $A$ for \texttt{shift\_cloud} (square) and for the measurement (circle).

The modeled absorptance for \texttt{shift\_cloud} and the measured mean value are plotted. For the measurements, no PDF can be derived. The distribution of the absorptance throughout the grid obtained from the \texttt{pdf\_cloud} and \texttt{hom\_cloud} is almost similar. For \texttt{shift\_cloud}, the maximum is observed at about 2.3%. The mean value is lower because there is a local maximum at 0.8%. The negative values are caused by fluctuations of the local irradiances due to the limited number of photons used in the MC model and to horizontal photon transport or other three-dimensional effects.
Chapter 9

Summary and Outlook

Within this work, the M-Fast-FSSP was developed, tested, and deployed in two field experiments. It overcomes serious problems of existing cloud drop sizing probes which are caused by a fixed sampling volume such as artificial broadening of the drop size distribution.

Using detailed microphysical airborne measurements of a specific case, the three-dimensional cloud structure was analyzed by several statistical methods, and model clouds were reproduced. Three-dimensional radiative transfer calculations were performed on the basis of the model clouds, and the results were compared with spectral radiation measurements.

M-Fast-FSSP

The major improvement of the new M-Fast-FSSP is a variable sampling volume which can be defined after the measurements have been taken. This was achieved by recording of additional signals with a revised data acquisition.

The artificial broadening of the drop size distribution observed by former FSSP versions is mainly caused by light intensity inhomogeneities of the laser beam within the sampling volume. When decreasing the sampling volume, the measured size distribution is less affected by artificial broadening. On the other hand, the number of drops which are used for accumulating the size distribution is reduced. Varying the sampling volume allows to balance the two requirements of sufficient drop counting statistics and homogeneity of the laser beam within the sampling volume. An extrapolation technique was developed which allows to estimate the natural width of the drop size distribution which is unbiased by instrumental artefacts.

The optical transfer matrices and the laser beam inhomogeneity of the M-Fast-FSSP were determined and a new calibration scheme was introduced. Thereby the optical transfer matrices were used to predict the shape and width of the measured distribution. The good agreement of the predictions with the measurements allowed to identify individual peaks resulting from the structure of the response curve of the instrument and from laser beam inhomogeneities.

Furthermore, a new method for determining the drop size dependent sampling volume, based on measurement data, was developed to improve the droplet concentration measurement, which is generally afflicted with large uncertainties for all FSSP types.

The M-Fast-FSSP was compared with a Fast-FSSP and other microphysical instrumen-
tation. Aircraft M-Fast-FSSP and Fast-FSSP data were consistent with respect to the liquid water content and the effective radius. Differences were observed for the shapes of the size distributions. Additionally, the M-Fast-FSSP was used on the platform of a tethered balloon. The therefore needed drop velocity was derived from an additional parameter which was recorded for this purpose. A good agreement with parallel sonic wind speed measurements was achieved.

Profiles of the width of the size distribution measured for the aircraft and balloon application differed substantially from previous studies. For FSSP-100 and Fast-FSSP measurements, a broadening of the drop size distribution with height above cloud base had usually been observed. This is in contradiction to condensational drop growth models. Applying the new extrapolation technique resulted in a constant or even decreasing width with height as predicted by the models.

Furthermore, it was shown that the size of the sampling volume has an impact on drop coincidences. For droplet concentration measurements, the effects of coincidences can be considerably reduced by decreasing the sampling volume.

Cloud Structure and Radiation

For a specific case, the impact of cloud spatial inhomogeneities on the spectral radiation field was studied. The main objective was to find methods for reproducing three-dimensional cloud fields when only airborne microphysical measurements are available. This is a rather common situation for field experiments since Radars and other remote sensing instruments for probing cloud structure are not always available.

The microphysical measurements along the flight track were used to derive the microphysical and macrophysical properties of the studied cloud layer, including its three-dimensional structure. One-point statistics was provided by profiles of LWC and of ∑(. A better characterization was achieved by introducing the two-dimensional probability density functions (PDFs) of LWC and ∑ which conserve the correlation between these quantities, and the layer cloud fraction. In this way, the microphysical and macrophysical description were separated. Moreover, the measurement variability is reflected in the PDFs.

In principle, the statistical significance of these data with respect to the entire cloud layer can only be determined from a large number of profile measurements. A quantitative measure based on standard deviations was introduced. For the studied case, a limited number of profiles was sufficient to characterize the layer.

Two-point statistics of LWC and of the spectral irradiiances were analyzed by using the power spectra and by calculating leap probability functions along a horizontal flight leg within the cloud layer. For both microphysical and irradiance measurements, a typical scale of 7-8 km was identified. A scale break at about 1 km was found in the irradiance measurements only. It is probably caused by radiative smoothing.

The derived cloud parameters were used as input for simple cloud reproducing algorithms. A homogeneous cloud layer (hom_cloud) was generated by distributing the average measured profile of LWC and ∑ over the grid. Next (pdf_cloud), the three-dimensional structure was considered by distributing LWC and ∑ randomly throughout the grid such that they are consistent with the measured two-dimensional probability density function. For this
model cloud, horizontal correlations were not considered. Therefore, a third model cloud (shift\_cloud) was introduced. Variations of cloud parameters in horizontal direction were implemented by shifting the average measured profile up- and downward based on a LWC time-series which was measured during horizontal in-cloud flight legs.

Neither of the three model clouds are expected to completely reflect the true physical nature of the clouds. The advantage of the three cloud algorithms in comparison with other schemes is the applicability to aircraft measurements without additional assumptions. The reproduced cloud fields are straightforward realizations of the measured statistical properties of the real cloud layer.

In the next step, the three model clouds were used as input for three-dimensional radiative transfer calculations in order to reproduce the observed radiation measurements. The three-dimensional radiative transfer model MYSTIC was used to calculate the field of the spectral irradiance at a wavelength within the range of the albedometer.

The best agreement of the modeled and measured mean irradiances was found when using the pdf\_cloud. The variability of the up- and downward irradiances was compared by using the probability density functions of the measured and modeled irradiance above and below the cloud layer. Only for the shift\_cloud where the horizontal cloud structure is considered, the measured and modeled variability of the irradiance are consistent.

The reflectance of the modeled cloud layer was higher than observed, the transmittance and absorptance lower for all three model clouds. For the shift\_cloud, the modeled absorptance (2\%) was closer to the measurements (4\%) than hom\_cloud (1\%) and pdf\_cloud (0.4\%).

Summarizing, different properties of the measured radiation field are best reproduced by different model cloud approaches. For reproducing profiles, the hom\_cloud and pdf\_cloud with one-point statistical input are appropriate whereas the shift\_cloud is needed to obtain the measured variability.

Outlook

As a further application of the M-Fast-FSSP, the droplet size distributions rather than bulk LWC and \( R_{\text{eff}} \) values have to be used as input for radiative transfer models to study the impact of the width of the size distribution on solar radiation and cloud radiative layer properties. Moreover, the balloon-based application offers a large potential for measurements of the effects of turbulence within clouds and at cloud interfaces, including the influences on the broadening of the drop size distribution and formation of precipitation. These processes are currently being discussed in literature (Pinsky and Khain, 2002 and 2003).

This work is only a starting point for detailed studies about the field of irradiances above, below and within heterogeneous cloud fields. The advantages of the three presented algorithms will have to be combined such that all properties of the radiation field are optimally reproduced by one model cloud. Furthermore, an application to broken cloud cases is desirable. Such a further development is currently under way (first results in Scheirer and Schmidt, 2004). Data from the INSPECTRO campaign are still being processed. A first overview of results is given by Kylling et al. (2004). So far, the radiative transfer was performed for only one wavelength. More wavelengths must be studied for a variety
of cloud scenarios in order to identify sources for the gap between measured and calculated absorptance. In this context, an extension of the albedometer wavelength range makes sense towards IR, because in this spectral range, various absorption effects, for instance from water, are expected.
## Appendix A

### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>absorptance</td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>albedo</td>
<td></td>
</tr>
<tr>
<td>$A_L$</td>
<td>laser sensitive area</td>
<td>mm²</td>
</tr>
<tr>
<td>$A_s$</td>
<td>sampling area</td>
<td>mm²</td>
</tr>
<tr>
<td>$Act$</td>
<td>activity of the FSSP-100</td>
<td></td>
</tr>
<tr>
<td>$\beta_{abs}$</td>
<td>absorption coefficient</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>$\beta_{ext}$</td>
<td>extinction coefficient</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>$\beta_{sca}$</td>
<td>scattering coefficient</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>$c_h$</td>
<td>layer cloudiness or cloud fraction</td>
<td></td>
</tr>
<tr>
<td>$C_{sca}$</td>
<td>scattering cross section</td>
<td>m²</td>
</tr>
<tr>
<td>$C_w(h)$</td>
<td>moist adiabatic condensate coefficient</td>
<td>g m⁻³ m⁻¹</td>
</tr>
<tr>
<td>$\chi$</td>
<td>scattering angle FSSP</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>drop diameter</td>
<td>μm</td>
</tr>
<tr>
<td>$\langle D^\alpha \rangle$</td>
<td>$\alpha$th moment of drop size distribution</td>
<td>μm$^\alpha$</td>
</tr>
<tr>
<td>$dA$</td>
<td>area element</td>
<td>m²</td>
</tr>
<tr>
<td>$dA_{\perp}$</td>
<td>horizontal area element</td>
<td>m²</td>
</tr>
<tr>
<td>$dM/dD$</td>
<td>mass distribution</td>
<td>g cm⁻³ μm⁻¹</td>
</tr>
<tr>
<td>$dN/dD$</td>
<td>number size distribution</td>
<td>cm⁻³ μm⁻¹</td>
</tr>
<tr>
<td>$dS/dD$</td>
<td>surface distribution</td>
<td>cm² cm⁻³ μm⁻¹</td>
</tr>
<tr>
<td>$d\Omega$</td>
<td>solid angle</td>
<td>sr</td>
</tr>
<tr>
<td>$\Delta\chi$</td>
<td>angular range of FSSP</td>
<td></td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>accumulation time interval for FSSP measurements</td>
<td>s</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>width of the Fast-FSSP sampling area</td>
<td>μm</td>
</tr>
<tr>
<td>$E$</td>
<td>spectral actinic flux density</td>
<td>W m⁻² nm⁻¹</td>
</tr>
<tr>
<td>$f_c$</td>
<td>ADC conversion factor from voltage to channels of the Fast-FSSP</td>
<td>V⁻¹</td>
</tr>
<tr>
<td>$f_i$</td>
<td>scaling factor for (M)-Fast-FSSP channel $i$, formula (5.13)</td>
<td>V⁻¹</td>
</tr>
<tr>
<td>$f_s$</td>
<td>sampling frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_k$</td>
<td>frequencies of the power spectrum</td>
<td>Hz</td>
</tr>
<tr>
<td>$F$</td>
<td>spectral irradiance</td>
<td>W m⁻² nm⁻¹</td>
</tr>
</tbody>
</table>
$F^\downarrow$ spectral downward irradiance \hspace{2cm} W m$^{-2}$ nm$^{-1}$
$F^\uparrow$ spectral upward irradiance \hspace{2cm} W m$^{-2}$ nm$^{-1}$
$F_{net}$ spectral net irradiance \hspace{2cm} W m$^{-2}$ nm$^{-1}$
$F_a$ spectral absorbed irradiance \hspace{2cm} W m$^{-2}$ nm$^{-1}$
$\Phi$ radiant flux \hspace{2cm} -
$H$ homogeneity of the laser beam light intensity within the sampling area \hspace{2cm} -
$I_0$ incident light intensity \hspace{2cm} W m$^{-2}$
$L$ radiance \hspace{2cm} W m$^{-2}$ sr$^{-1}$
$LWC$ liquid water content \hspace{2cm} g m$^{-3}$
$LWP$ liquid water path \hspace{2cm} g m$^{-2}$
$\lambda$ wavelength \hspace{2cm} $\mu$m
$\Lambda$ leap probability function \hspace{2cm} -
$m$ 'Reference’ Amplification Factor for M-Fast-FSSP \hspace{2cm} -
$M$ correction factor for FSSP-100 concentration measurements (5.1.5) \hspace{2cm} -
$MDV$ median volume diameter \hspace{2cm} $\mu$m
$N$ concentration \hspace{2cm} cm$^{-3}$
n total drop rate \hspace{2cm} s$^{-1}$
n$_d$ drop rate in the sampling area \hspace{2cm} s$^{-1}$
n$_i$ valid drop rate within size bin $i$ \hspace{2cm} s$^{-1}$
n$_m$ valid drop rate for $m$ \hspace{2cm} s$^{-1}$
$\nu$ refractive index \hspace{2cm} -
$p_h$ two-dimensional PDF of the $LWC$ and $R_{eff}$ \hspace{2cm} -
$P_{sc}$ power of scattered light \hspace{2cm} W
$Pow_{LWC}(f_k)$ One-sided Power Spectrum of the $LWC$ \hspace{2cm} (g m$^{-3}$ Hz$^{-1}$)$^2$
$PSA$ Particle Surface Area \hspace{2cm} cm$^2$ cm$^{-3}$
$R$ reflectance \hspace{2cm} -
$R_{eff}$ effective drop radius \hspace{2cm} $\mu$m
$r(i)$ $n_m/n$ for each channel $i$ \hspace{2cm} -
$\rho$ (water) density \hspace{2cm} g cm$^{-3}$
$R(x, z)$ array of the ‘Reference’ voltage \hspace{2cm} V
$R_0$ ‘Reference’ voltage offset \hspace{2cm} V
$\bar{R}_i(x, z)$ $R(x, z)$ converted to channels, formula (5.12) \hspace{2cm} V$^{-1}$
$S(x, z)$ array of the ‘Signal’ voltage \hspace{2cm} V
$S_0$ ‘Signal’ voltage offset \hspace{2cm} V
$\hat{S}_i(x, z)$ $S(x, z)$ converted to channels, formula (5.11) \hspace{2cm} V$^{-1}$
$\sigma_g$ global $LWC$ variability (section 6.2.1) \hspace{2cm} g m$^{-3}$
$\sigma_l$ local $LWC$ variability (section 6.2.1) \hspace{2cm} g m$^{-3}$
$T$  
transmittance  

$T$  
temperature  °C  

$T_m$  
optical transfer matrix  

$TAS$  
true air speed  m s⁻¹  

$\theta_s$  
solar zenith angle (SZA) °  

$\tau$  
optical thickness  

$v_0$  
drop velocity through the FSSP sampling tube  m s⁻¹  

$V_L$  
laser sensitive volume  cm³  

$V_L^*$  
effective laser sensitive volume for coincident valid drops  cm³  

$V_s$  
sampling volume  cm³  

$w_0$  
beam waist  μm  

$\omega_0$  
single scattering albedo  

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Appendix B

Glossary

ACTOS  Airship-borne Cloud Turbulence Observation System
AFDM  Actinic Flux Density Meter
BALTEX  BALTic sea EXperiment
BBC  BALTEX Bridge Campaign
CCD  Charge-Coupled Device
CDS  Cloud Drop Spectrometer
CLIWA-NET  CLoud LIquid WAter NETwork
CPC  Condensation Particle Counter
CPU  Central Processing Unit
CVI  Counterflow Virtual Impactor
DOF  Depth Of Field
DTV  Detection Threshold Voltage
FPGA  Field Programmable Gate Array
FFT  Fast Fourier Transform
FSSP  Forward Scattering Spectrometer Probe
GPS  Global Positioning System
INSPECTRO  INfluence of clouds on the SPECTral actinic flux in the lower TROposphere
IfT  Leibniz-Institut für Troposphärenforschung (Institute for Tropospheric Research), Leipzig, Germany
IfU  Institut für Meteorologie und Klimaforschung (Institute for Meteorology and Environmental Research), Bereich Atmosphärische Umweltforschung (Branch Atmospheric Environmental Research)
ICA  Independent Column Approximation
IR  InfraRed radiation
LACE  Lindenbergaerosol Characterization Experiment
LES  Large Eddy Simulation
LDV  Laser Doppler Velocimetry
LIDAR  Light Detecting And Ranging
LVDS  Low Voltage Differential Signaling
MCS  Multi-Channel Spectrometer
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>MYSTIC</td>
<td>Monte carlo code for the physically correct Tracing of photons</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NIP</td>
<td>Normal Incidence Pyrheliometer</td>
</tr>
<tr>
<td>NIR</td>
<td>Near InfraRed radiation</td>
</tr>
<tr>
<td>OAP</td>
<td>Optical Array Probe</td>
</tr>
<tr>
<td>PCASP</td>
<td>Passive Cavity Aerosol Spectrometer Probe</td>
</tr>
<tr>
<td>PCI</td>
<td>Peripheral Component Interconnect (personal computer bus)</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PDPA</td>
<td>Phase Doppler Particle Analyzer</td>
</tr>
<tr>
<td>PHA</td>
<td>Pulse Height Analyzer</td>
</tr>
<tr>
<td>PMS</td>
<td>Particle Measuring Systems, Inc., Boulder, USA</td>
</tr>
<tr>
<td>PP</td>
<td>Plane-Parallel</td>
</tr>
<tr>
<td>PSM</td>
<td>Particle Spacing Monitor</td>
</tr>
<tr>
<td>PSP</td>
<td>Precision Spectral Pyranometer</td>
</tr>
<tr>
<td>PVM</td>
<td>Particle Volume Monitor</td>
</tr>
<tr>
<td>RADAR</td>
<td>RAdio Detection And Ranging</td>
</tr>
<tr>
<td>RTE</td>
<td>Radiative Transfer Equation</td>
</tr>
<tr>
<td>RTM</td>
<td>Radiative Transfer Model</td>
</tr>
<tr>
<td>SCSI</td>
<td>Small Computer System Interface</td>
</tr>
<tr>
<td>SODAR</td>
<td>SOnic Detection And Ranging</td>
</tr>
<tr>
<td>SZA</td>
<td>Solar Zenith Angle</td>
</tr>
<tr>
<td>UTC</td>
<td>Universal Time Coordinated</td>
</tr>
<tr>
<td>UV</td>
<td>UltraViolet radiation</td>
</tr>
<tr>
<td>VAR</td>
<td>Velocity Acceptance Ratio</td>
</tr>
<tr>
<td>VELIS</td>
<td>VEHICLE mounted Lidar System</td>
</tr>
<tr>
<td>VHDL</td>
<td>Very high speed integrated circuit Hardware Description Language</td>
</tr>
<tr>
<td>VIPS</td>
<td>Video Ice Particle Sampler</td>
</tr>
<tr>
<td>VIS</td>
<td>VISible radiation</td>
</tr>
<tr>
<td>3D</td>
<td>three-dimensional</td>
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</table>

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Appendix C

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Appendix D

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