Ground- and satellite-based multi-view photogrammetric determination of 3D cloud geometry

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GROUND- AND SATELLITE-BASED MULTI-VIEW PHOTOGRAMMETRIC DETERMINATION OF 3D CLOUD GEOMETRY

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH
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2003
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In this doctoral thesis, the possibilities of ground- and satellite-based multi-view measurements of clouds with modern photogrammetric methods are examined, with the objective to derive cloud-base/-top heights and motion. These parameters are important for a better description of clouds for nowcasting, numerical weather prediction and climate research. The presented work is part of the EU projects Cloudmap and Cloudmap2.

For the ground-based data acquisition, a new ground-based multi-camera system was developed. The camera system consists of at least two commercial digital CCD cameras, with a horizontal distance of about 500-1000 m, each connected to a laptop computer for camera control and image storage and to a radio clock for high-precision time synchronization. The stereo-photogrammetric method to calculate height and motion of the cloud-base included the precise determination of the interior and exterior orientation parameters of the cameras which was carried out with an in-house close-range photogrammetric testfield and an on-site orientation with GPS and stars. The cameras were installed at Mels, Switzerland, in October 1999 during the Mesoscale Alpine Programme (MAP) and at Zürich-Kloten Airport, Switzerland, in September 2001 and April 2002, in coincidence with other cloud measurement instruments (i.e. ceilometer, lidar, IR camera and soundings) and satellite overpasses of ERS-2 and EOS-Terra.

To calculate cloud-base and cloud-top height automatically, different image processing steps, including image preprocessing, feature extraction, image matching, blunder detection and further postprocessing, were applied to the multi-view images. Existing photogrammetric methods were thereby tested on the various cloud images and adapted when necessary to the specific problems encountered with clouds. First, a Wallis filter was used for radiometric equalization of the images and contrast enhancement. Suitable matching features were then selected with the Förstner or Harris operator for points and with the Canny operator for edges, respectively. If a cloud mask was available, it was used to thin out the feature set before matching to include only cloud features. The hierarchical matching approach with the Multi-Photo Geometrically Constrained (MPGC) LSM software, developed at our Institute, was successfully applied to the cloud images. For blunder detection, the matching results were quality-controlled with absolute and relative tests on the LSM statistics. The matching results illustrated that the MPGC LSM method can be used for the task of cloud matching, if applied with the necessary preprocessing, match point approximation and quality control strategies. It was further shown how a third camera can facilitate the ground-based cloud-base height retrieval through the additional geometric constraints.

Seven ground-based cases were analyzed in detail with the cloud-adapted matching algorithm. Thereby, different matching strategies were tested, including use of original images versus preprocessed images, use of more than two cameras and sequence-based analysis. As validation, the results were compared with semi-automatically measured points and with several other instrument data like radiosondes, ceilometers, lidars and IR cameras. Comparisons with these data
have shown a good correspondence for the analyzed cases. The stereo camera system was able to retrieve accurate height values of cloud features for most cloud situations with relatively small standard errors (i.e. from a few meters for low clouds to about 100-150 m for high clouds at 10-12 km altitude). For most clouds, these stereoscopically matched features are a good proxy for the bottom boundaries of the clouds because most clouds become optically thick within a few hundred meters from their boundaries.

For the satellite part, multi-view images from MISR (on board EOS Terra), ASTER (on board EOS Terra) and ATSR2 (on board ERS-2) were used. As stereo image pairs from polar-orbiting satellites are never perfectly synchronous (i.e. time delay of some seconds between the image acquisition from the different viewing angles), the height error of the cloud-top heights, introduced by the along-track motion component, was corrected with cloud-top winds extracted from Meteosat-6 5-minute/10-minute rapid scan and Meteosat-7 30-min data. For MISR, with nine viewing angles, this height correction is only needed when two camera views or three symmetric views are taken. With at least three images from non-symmetric cameras, it is possible to directly separate the along-track parallax (due to cloud height) from the along-track wind contribution (due to cloud motion).

Four satellite-based cases with coincident stereo measurements of ASTER, MISR and ATSR2 and Meteosat-6/-7 image sequences were treated in detail. The results were compared to other operational cloud-top height and motion products as well as to radiosonde and ground-based cloud radar data. Thereby, the stereo cloud-top heights proved to be in very good correspondence (i.e. within 200-300 m) with the radar and radiosonde measurements, with the advantage that they depend only on basic geometric relationships of observations of cloud features from at least two different viewing angles and on the texture of these cloud features, while other cloud height estimation methods are dependent on knowledge of additional atmospheric parameters, like cloud emissivity, ambient temperature or lapse rate. As an interesting matching validation option, it was shown that, by chance, the cloud motion error for the MISR AN-AF and ASTER stereo cloud-top heights is approximately the same, independent of the actual cloud height and cloud motion. Therefore, it was possible to evaluate the accuracy of MISR AN-AF matching for one coincident ASTER-MISR case over Zürich-Kloten, independent of artifacts due to the subsequent wind correction.

Finally, three case studies of coincident ground- and satellite-based retrieval of cloud-base/cloud-top height and motion are presented. The case studies illustrated validation of satellite-based cloud-top height retrievals for vertically thin clouds with ground-based imagers. The described 3D cloud geometry data sets will be further used in the project Cloudmap2 for modelling and visualization studies. Together with the experiences from other ongoing cloud research projects on the assimilation of existing and new in-situ, ground-based and satellite-based cloud data into numerical weather prediction (NWP) models, it will significantly improve our understanding of cloud parametrization and representation in NWP and global climate models.
Zusammenfassung


Acknowledgments

“I aîme les nuages... les nuages qui passent... là-bas... là-bas... les merveilleux nuages !”
“I love the clouds... the clouds that pass... above and beyond... the marvellous clouds !”
Charles Baudelaire, 1862

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Acronyms

**AATSR** Advanced Along-Track Scanning Radiometer

**AGL** Above ground level

**AGP** Ancillary Geographic Product

**aLMo** Alpines Lokalmodell

**ARM** Atmospheric Radiation Measurement Program

**ASL** Above sea level

**ASTER** Advanced Spaceborne Thermal Emission and Reflection Radiometer

**ATBD** Algorithm Theoretical Basis Document

**ATSR** Along-Track Scanning Radiometer

**CBH** Cloud-base height

**CBW** Cloud-base wind

**CCD** Charge Coupled Device

**CGM** Camera Geometric Model

**CMOS** Complementary Metal Oxide Semiconductor

**CTH** Cloud-top height

**CTP** Cloud-top pressure

**CTW** Cloud-top wind

**DAAC** Distributed Active Archive Center

**DLR** Deutsches Zentrum für Luft- und Raumfahrt; German Aerospace Center

**DSM** Digital surface model

**DTM** Digital terrain model

**FORM** Föhn im Rheintal während MAP

**GBT** Gridded Brightness Temperature

**GCM** Global Climate Model

**GOES** Geostationary Observational Environmental Satellite
IGP  Institute of Geodesy and Photogrammetry ETH Zuerich
JPL  Jet Propulsion Laboratory
LMD  Laboratoire de Météorologie Dynamique
LSM  Least squares matching
MAP  Mesoscale Alpine Programme
MISR  Multi-angle Imaging SpectroRadiometer
MPGC  Multi-Photo Geometrically Constrained Matching
MSG  Meteosat Second Generation
NOAA  National Oceanic and Atmospheric Administration
NWP  Numerical weather prediction
RSCS  Range-squared corrected backscatter signal
SEVIRI  Spinning Enhanced Visible and Infrared Imager
SIO  Scripps Institute of Oceanography
SOM  Space Oblique Mercator
SOP  Special Observing Period
TSI  Total Sky Imager
WMO  World Meteorological Organisation
WSI  Whole Sky Imager
Chapter 1

Introduction

1.1 Motivation

Clouds, which have a strong impact on both the total incoming radiation at the Earth’s surface and the reflected radiation above the cloud field, are an important component in the earth radiation budget. As such, they also play a pivotal role in the interaction between the Earth’s climate and anthropogenic inputs, particularly the greenhouse gases. Accurate global measurements of the location, distribution and properties of clouds are therefore necessary, for nowcasting and weather forecasting as well as for global climate change studies, as described in the rationales of the EU projects Cloudmap and Cloudmap2 (Cloudmap, 2002; Cloudmap2, 2002).

The Cloudmap project developed algorithms for several cloud-top products (height, type, optical thickness, effective droplet size), especially for cirrus and contrail clouds, from existing and new sensors, using three different techniques (brightness temperature with CO2 slicing method, stereoscopy and oxygen A-band). These new cloud-top products were validated using airborne sensor flights and ground-based remote-sensing instruments. Cloudmap ended in January 2001 and is now continued by the EU Framework Programme 5 (FP5) project Cloudmap2 (February 2001 to January 2004). The objectives of Cloudmap2 are to produce and exploit value-added remote sensing data products on macroscopic (cloud-top height/pressure, cloud amount, cloud type, cloud-top motion) and microscopic (cloud optical depth, cloud albedo, cloud droplet effective radius, cloud droplet/crystal size distribution) cloud properties and water vapor distributions in order to improve the characterization of cloud processes within weather and climate models.

For acquiring global cloud coverage satellite-based methods are used, but they have to be calibrated and validated with ground-based measurements to understand their accuracies and error structures. Ground-based measurements, moreover, are important in their own right as initialization data to global and regional Numerical Weather Prediction (NWP) models and Global Climate Models (GCMs). The role of this doctoral research, as part of the Cloudmap and Cloudmap2 projects, is focussed on multi-view photogrammetric retrieval of cloud height and motion both
from the ground and from satellites.

Cloud properties are not well characterized with the existing observational networks. At most climate stations of the national networks, cloud macroscopic properties, including cloud cover, cloud type and cloud-base height, are still visually observed. At many airports, in addition to the visual observations, ceilometer measurements are used to determine cloud-base height automatically and continuously. Overall, the infrequent, spatially non-uniform, subjective and sparse point observations of clouds do not meet the user requirements. According to the WMO, “Guide to Meteorological Instrumentation and Methods of Observation”, an average vertical resolution of 30 m, a vertical accuracy of 10 m for clouds below 100 m and 10% for clouds above 100 m, in a height range between 30 m and 30 km are given as the requirements for cloud-base height use in operational meteorology (Hans Roozekrans, personal communication). No specific number for time resolution is mentioned; however, if operationally needed, frequent (or even nearly continuous) recording is advised. It has to be remarked that the vertical accuracy of any measurement technique is difficult to determine since there is no clear definition for cloud boundaries yet. So far, WMO still holds to the “old fashion” synops output as generated by the human observers and any automatic measurements have to be translated to this format; however, recent WMO recommendations propose to change these practices in the near future (Van der Meulen, 2002). The user requirements for cloud-top height were evaluated at a Cloudmap User Workshop (Roozekrans and de Valk, 2001) for three categories of users, “nowcasting/weather prediction”, “NWP and global climate models” and “climate research”. From operational forecasters, a time resolution of 15-30 min, a horizontal resolution of 1-5 km and a vertical resolution of 100-300 m are required for cloud-top height, with a standard error of 10-30 % and a timeliness of maximum 10 min. For modellers, the time resolution (15 - 60 min), the vertical resolution (100 m) and the standard error (10 %) are comparable requirements while the timeliness (maximum 1h) and horizontal resolution (< 50 km) are less strict than for operational forecasting. For climate research, no constraints are given for the timeliness and a much lower temporal resolution (1-3 h) is required. The horizontal (< 50 km) and vertical (100-500 m) resolution, as well as the standard error (10-30 %) are similar requirements to the other two user groups. Overall, it has to be critically remarked that these user requirements are only rough estimates and present an average result over several interviewed users. The values of the user requirements will be concretized more quantitatively as soon as more of the new cloud products will be operationally used in forecasting, modeling and climate research.

To date, cameras and photogrammetric methods are rarely used within the ground-based observational networks. Recent developments in the digital camera market, including lower prices and larger image formats, are leading to a revival of the idea of photogrammetric cloud observation station networks, which was already in discussion 100 years ago during the International Cloud Year 1896/1897 (Koppe, 1896). Operational use of analog images was not practical for most applications due to the enormous amount of time necessary to analyze a single time step by first scanning stereo image pairs with a photogrammetric scanner and then finding correspond-
ing points in the images by manual measurements. The new digital systems have the major advantage of reducing significantly processing time down to minutes, which gives them the potential of deriving cloud parameters in near-realtime. Spatially and temporally high-resolution three-dimensional data in the visible and near infrared from a ground-based digital imager system would nicely complement existing observations of macroscopic cloud parameters. For stereo camera systems, automatic, faster and more reliable matching methods to solve the correspondence problem are a second advantage. Finally, there is a qualitative advantage of data from a ground-based photogrammetric system: these data are easier to interpret visually for a forecaster and to link with the current synoptic situation than the point measurements from active remote sensing instruments like ceilometers, lidars and radars.

If ground-based stereo images are taken in coincidence with multi-view satellite data, cloud objects can be simultaneously analyzed from the bottom and the top. With vertically thin clouds (e.g. thin cirrus, contrails) the ground-based cloud-base height (CBH) results are a perfect validation for the satellite-based cloud-top height (CTH) results. For more vertically extended clouds the data sets from the top and the bottom allow a description of the cloud boundaries, which can be used in cloud models and very high resolution NWP models for three-dimensional modeling of clouds. The more realistic 3D representation of clouds in NWP models and GCMs has then a positive impact on their radiation and humidity modeling.

With the launch of the EOS-Terra platform in December 1999 two new multi-view satellite sensors, the Multi-angle Imaging SpectroRadiometer (MISR) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), became operational. They offer additional features to the existing multi-view sensor ERS2-ATSR2 in terms of number of viewing angles (two for ATSR2 versus nine for MISR) and spatial resolution (1 km for ATSR2 versus 15 m for ASTER and 275 m for MISR). While MISR was primarily designed for atmospheric studies, ASTER is exceptionally used for cloud mapping in this investigation and normally used for land surface studies and terrain modelling. As ATSR2, MISR and ASTER are all polar-orbiting systems, they do not provide the necessary temporal resolution for the forecasters. A sufficient time resolution would only be possible with a stereo system composed of two geostationary satellites, with the additional advantage of removing the effects of cloud motion as the paired images could be taken simultaneously.

Overall, given the progress of digital photogrammetry, there is a large potential of multi-view sensors and photogrammetric methods to be used in more atmospheric science applications in the near future. In the next section, history, we will first take a look back at the beginnings of cloud photogrammetry in the 19th century and its evolution from ground-based to aerial- and satellite-based systems. The section on latest developments in cloud photogrammetry will then underline the benefits of these techniques and recent advances to allow a further spread among meteorological users.
1.2 Review of photogrammetric cloud measurements

1.2.1 Manual processing

Cloud photogrammetry is not a new topic. Many researchers have worked with cloud photographs to derive cloud parameters, mainly for climatological analysis. Analog stereo images of clouds have already been taken and analyzed more than one hundred years ago (Koppe, 1896). Height values were often calculated from simultaneous theodolite observations of the same cloud point with a base of a few hundred meters to a few kilometers between the theodolites. To point the two theodolites at the same cloud feature communication over the phone was needed, which was understandably quite difficult and time-consuming, especially in fast-moving cloud situations where the cloud shapes changed within seconds. With the development of photogrammetric theodolites (“Phototheodolit”) (Koppe, 1896), the problem was reduced to synchronization of the two image acquisitions, as the corresponding cloud points were then found and analyzed on an optical measurement table. The photogrammetric cloud theodolite of Koppe (Figure 1.1) was improved by A. Sprung to allow precise synchronous shutter releases of both camera systems by an electric signal (Süring, 1926). Systematic photogrammetric cloud research with multi-year records of stereo cloud photos and derived products, such as cloud-base heights and cloud movement, began soon after the first International Cloud Year in 1896/1897 (e.g. Sprung and Süring, 1903; Süring, 1922). At that time clouds provided the only source of information on upper atmospheric flow. Measurements were focussed on the derivation of cloud height, cloud speed and direction of cloud motion, while studies on the three-dimensional form of the clouds were started much later (Süring, 1936).

Räthjen (1931) subsequently used ground- and aerial-based systems to assess the shape and structures of cloud systems in support of forecaster nowcasting. Single aerial-based systems, as well as non-geostationary satellite systems, have the problem that no synchronous stereo pairs can be acquired. Small time delays of a few seconds to minutes have a substantial influence on the shape of cloud boundaries. Räthjen (1931) also mentions the possibility of using the width of the airplane wings as the base with a camera mounted at the end of each wing. Due to the small base length this method does not allow precise results.

Bradbury and Fujita (1968) show the applicability of hemispheric stereo camera systems, so-called whole sky systems, in a small prototype network. They proved that cloud-base height and cloud-base motion can be obtained from such systems and used as validation data for satellite-based cloud property retrievals.

Before the launch of the first satellite platforms stereo photographs were only taken from ground-based systems and from low- and high-flying aircrafts equipped with aerial mapping cameras. The aerial coverage for cloud mapping was thereby limited because of the ceiling of the photogrammetric altitude. TIROS 1 as the first weather satellite, launched in 1960, completely changed the observation of clouds. Pioneer studies in this respect were the stereoscopic analysis of NIMBUS II APT images by Ondrejka and Conover (1966) and Kikuchi and Kasai (1968) and the use of
Apollo 6 pictures for stereo-height computations (Whitehead et al., 1969; Shenk et al., 1975).

In 1974, the first operational geosynchronous satellite SMS-1 was launched and positioned at 75° W. With the successful launch of SMS-2 in 1975, positioned at 107° W, scan-synchronized stereo pairs were acquired at the regular operational frequency of 30 minutes. The conceptual part is described in Bristor and Pichel (1974) while the analysis of the hard copy images with aerial stereo-photogrammetric techniques is shown in Minzner et al. (1978). The geostationary stereo analysis of clouds continued with the launch of the National Oceanic and Atmospheric Administration (NOAA) Geostationary Observational Environmental Satellite (GOES) GOES-East and GOES-West satellites in the late 1970s (Hasler, 1981) and included further combinations such as GOES-West and the Japanese GMS-1 geostationary satellite (Fujita, 1982) or GOES-East and NOAA polar-orbiting satellites (Hasler et al., 1983).

1.2.2 Automated processing

A major step forward in ground-based cloud photogrammetry was marked with the introduction of digital cameras. The first field measurements with a digital hemispheric imager were performed with the Whole Sky Imager (WSI) instrument (Johnson et al., 1989; Shields et al., 1999) at some of the Atmospheric Radiation Measurement (ARM) Program sites (Stokes and Schwartz, 1994). The first stereo experiment with digital cameras was done by Allmen and Kegelmeyer (1996). They analyzed data acquired with a pair of WSI's, which had been fielded in New Mexico. Due to the large base chosen, and consequently larger border distortions within the overlap area, as
well as inaccuracies in the exterior camera orientation, matching of the stereo pairs was difficult. Furthermore, the matching process was much slower than today as a result of slower computer processors. Another set of commercial digital cloud imagers available today, the Total Sky Imagers (TSI), are based on the same principle as used by Bradbury and Fujita (1968) with the camera pointing vertically downwards on a spherical mirror that is reflecting the sky hemisphere (Yankee Environment Systems Inc., 2002). So far, accurate on-site calibration and orientation of the system has yet to be demonstrated (Mark Beaubien, personal communication) and pre-operational tests at one of the MeteoSwiss ANETZ sites (MeteoSwiss, 2002) show some significant logistical problems requiring daily maintenance of the system (e.g. cleaning of the mirror).

Several satellite-based investigations of severe thunderstorms, hurricanes and cloud emissivity demonstrated the importance of stereo imagery as a diagnostic tool for satellite meteorology and cloud remote sensing during the last decades (Lancaster et al., 2003). But only with the advent of multiprocessor computer systems and the use of more sophisticated matching algorithms (as described later in this section), the multi-view cloud height and motion retrieval could be largely automated (Hasler et al., 1991; Campbell and Holmlund, 2000; Moroney et al., 2002). Over Europe, there is still no suitable possibility for geostationary stereo analysis. In recent years, however, several instrument payloads providing multi-angle measurement capabilities have been placed in low earth orbit. Lorenz (1983) described the two possible configurations to acquire multi-view images from polar-orbiting platforms, either with a one-satellite version at different times or with a two-satellite version synchronously. Only the former principle, one-satellite version, has been realized until today, e.g. the along-track scanning radiometer (ATSR) series (ATSR on board ERS-1, ATSR2 on board ERS-2, AATSR on board Envisat) or the Multi-angle Imaging SpectroRadiometer (MISR) on board EOS-Terra launched in December 1999.

Hasler et al. (1991) developed a fully automatic stereo analysis technique based on cross-correlation. The stereo image pairs were first preprocessed primarily to strengthen the pattern recognition used in the matching algorithm. In the processing, every pixel was attempted to be matched and surface continuity constraints on the resulting cloud-top heights were then used in postprocessing to exclude local elevation discontinuities. Many cloud surfaces proved to be difficult to process, especially steep slopes within cloud fields, discontinuities at cloud edges and cirrus clouds with very little structure.

Campbell (1998) developed an algorithm to derive both height and motion from asynchronous satellite stereo images using a purely geometrical technique. Case studies were presented from GOES East/West in combination with NOAA AVHRR and from Meteosat-5 in combination with Meteosat-7. Near-simultaneous multi-angle imagery from MISR allow the application of the technique described in Horvath and Davies (2001) to simultaneously retrieve cloud height and motion from matched triplets of non-symmetric views.

Several matching constraints can be introduced with additional cloud-related products, either from the same sensor or from external data. Mahani et al. (2000) described an efficient method for estimating cloud-top heights by profiting of the relationship between height and infrared bright-
ness temperature of cloud tops. Of course, this method is only applicable for multi-view sensors equipped with thermal IR channels.

In Muller et al. (2002), Moroney et al. (2002) and Zong et al. (2002), the operational matching methods and strategies of the MISR L2TC product are explained in detail. In general, the Nested Maxima (NM) matcher is used for the cloud motion retrieval while the multi-point M2/M3 (M23) matcher is applied for a refined cloud-top height retrieval. For some case studies, the P-Gotcha matching algorithm was run for comparison. The preliminary examples shown in Muller et al. (2002) which compare the operational M23 matches with P-Gotcha matches show close agreement fit between the matchers, however, the a priori expectable superiority of the P-Gotcha matcher does not appear in the results at all.

Shi et al. (2002) used the so-called linear correlation matching classification (LCMC) algorithm for MISR cloud detection over ice and snow. Compared with the operational MISR L2TC matching results, they report to receive a better coverage and more robust results with the LCMC algorithm.

Remote sensing data, both ground- and satellite-based, became more and more important for data assimilation and verification of NWP models and GCMs in recent years. A good review of preliminary successful use of remote sensing data in numerical modelling is given in Gustafsson et al. (2002). According to their outlook, present and planned operational satellite observing systems will give substantial contributions to meet several of the observation requirements for regional NWP in the near future. The various requirements thereby depend on the spatial scale of the models. Next to the new cloud observation techniques, new assimilation methods will be required for these unconventional data for their assimilation into regional NWP models.

1.3 Research objectives

The aim of this doctoral research is to examine cloud-top and cloud-base height and motion retrievals using multi-view photogrammetry with today’s satellite- and ground-based systems. These macroscopic cloud parameters are important for better description of clouds for nowcasting and NWP models.

The work can be divided into four main parts: 1) development of a ground-based camera system consisting of commercial off-the-shelf and in-house constructed components; 2) modification of existing matching algorithms to the special characteristics and problems of clouds; 3) application of the new cloud-adapted methods to both ground- and satellite-based images to derive cloud-base and cloud-top heights and cloud motion for meteorological applications; and 4) comparison and validation of the derived cloud parameters with other coincident measurements.

For the new ground-based system, which consists of at least two cameras, the chosen commercial camera should fulfill the camera and sensor requirements necessary for this application and, if possible, reduce the problems of saturation and insufficient contrast within clouds. Furthermore, the system should be protected against any environmental influences (i.e. sun effects, severe
weather) and the cameras need to be synchronized to avoid cloud shape differences between the stereo images. The camera modelling procedure must include the derivation of both the interior and exterior orientation parameters. The interior orientation can be determined using close-range photogrammetric practices with a three-dimensional testfield in the laboratory. In the field, it should also be possible to recalibrate the system to detect any interior orientation changes (e.g. with star observations). For the exterior orientation the process is more difficult because the common method from aerial photogrammetry of using ground control points (GCPs) cannot be applied as there are usually no GCPs available in the field of view of the camera when looking vertically towards the sky. So, “sky control points” have to be used, consisting of either natural objects (e.g. stars) or artificial objects (e.g. planes, helicopters or balloons). Another option for the determination of the orientation angles would be the use of tilt sensors at the tripod. The exterior calibration method should be as simple, fast and reliable as possible and allow a periodic recalibration to detect any orientation changes.

The matching of clouds presents various problems: low texture or saturation within clouds, small signal-to-noise ratio, poor definition of cloud edges, surface discontinuities and gaps, transparent or semi-transparent surfaces, illumination differences, perspective differences, multiple solutions, occlusions and motion-related problems like shape changes for the non-synchronous satellite-based multi-view images. In a first step, it had to be evaluated if these difficulties can be handled in a sufficient way by the existing Multiphoto Geometrically Constrained Least-Square Matching (MPGC) algorithm developed at our Institute. Additionally, appropriate matching strategies and alternative approaches that do not require good approximations (i.e. first starting positions) and combine global with local matching had to be considered. The final methodology should include both preprocessing to optimize the conditions for the matching algorithm and objective quality criteria to detect as many blunders as possible.

If a satellite sensor provides multispectral information, matching can be performed with the different channels and the results compared. Preliminary studies show that sometimes, by comparing the stereo results of various spectral channels, different cloud layers can be detected with different channels, providing an attractive method for observing multilayer clouds. As there are currently no operational satellite sensors that provide simultaneous acquisition of stereo pairs, along-track parallax due to cloud motion has to be eliminated before the cloud height calculation. A new method for this motion correction is presented, which is based on tracked cloud-top winds from geostationary satellites.

Validation strategies for the new ground- and satellite-based cloud height products are also important. Three methods are considered in the current study: 1) visual control at a digital photogrammetric station, 2) validation with semi-automatically measured points and 3) validation/comparison with simultaneously acquired data from radiosonde ascents, ceilometers, thermal infrared cameras, ground-based lidars and radars.
1.4 Outline

The thesis starts with the description of the newly developed ground-based camera system, including its sensor characteristics, the setup of the cameras and the calibration process (Chapter 2). In Chapter 3, the cloud-adapted matching methods and strategies are explained. These algorithms are applied both to ground- and satellite-based stereo cloud images. In the second part of the thesis, the application part, results from the ground-based (Chapter 4), satellite-based (Chapter 5) and combined ground-satellite (Chapter 6) analyses are shown. The ground-based system analysis using a few case studies demonstrates the applicability, accuracy and limitations of our imager system for cloud measurements. After an introduction of the relevant satellite sensors, the satellite-based analysis considers the main similarities and differences between ground- and satellite-based height estimation. Additionally, the satellite-based processing includes an evaluation of spectral and angular differences and an investigation of the motion errors in the polar-orbiting along-track stereo images. Successful simultaneous image acquisitions from the ground and from satellites are rare. We present three ground-based data sets in coincidence with EOS-Terra and ERS-2 overflights, one of them including an on-demand ASTER image acquisition. Finally, Chapter 7 summarizes the main findings and provides an outlook on the potential of digital cameras in observational networks and on the ongoing cloud research objectives of Cloudmap2, which will make use of the three-dimensional data sets from the combined ground- and satellite-based analysis.
Chapter 2

Ground-based camera system

To date, digital cameras and photogrammetric methods are rarely used within the ground-based meteorological observation networks. Using a single imager, cloud amount and distribution may be measured. Fully automated ground-based digital Whole Sky Imagers (WSI), developed by the Scripps Institute of Oceanography (SIO) at the University of California, San Diego, beginning in the early 1980's, have been used for these applications for many years, but only a few of these imagers were actually fielded for operational use. These WSIs acquire image data once a minute at several sites globally (e.g. ARM sites, Deutscher Wetterdienst at Potsdam) in order to automatically determine cloud amount and distribution (Johnson et al., 1989; Shields et al., 1998). Additionally, cloud-base height and three-dimensional cloud-base motion can be measured if at least two ground-based digital cameras are arranged in a stereo configuration. However, none of the operational hemispheric digital imagers around the world is currently set up in a stereo configuration. To evaluate the capability of a ground-based stereo-photogrammetric system to measure cloud-base height and motion automatically, our own prototype stereo imager system, called “skycam”, was developed. Theoretically, two cameras are sufficient for this task; we will explain in Chapter 3 how our cloud-base height and motion retrieval could be optimized by the use of three, or even four, cameras in an optimal geometric arrangement.

The design of the system started with the evaluation of a suitable commercial off-the-shelf camera and image sensor for this application. The hardware and software of the system had to control the configuration of the camera (i.e. exposure time, aperture and ISO setting), the shutter release and the image storage, while guaranteeing precise synchronization between multiple cameras. The availability and performance of the image storage had to be considered to allow the continuous acquisition of longer time series. A wide-angle camera lens was required for achieving an acceptable overlap area even for lower clouds. To avoid image deterioration due to environmental factors (e.g. sun, dust, rain, condensation, etc.), several additional features were built into the system to protect the camera. For the field setup of the cameras, several trade-offs had to be considered. To ensure precise three-dimensional cloud parameter results, a sophisticated geometric
calibration and orientation process for both the interior and exterior orientation of the cameras was developed. The calibration includes determination of the most significant systematic errors, like focal length, principle point offset, lens distortion and non-orthogonality of chip axes. Finally, two other influence factors, atmospheric refraction and sun blooming, had to be investigated and their effects minimized. In the following sections, the different components and aspects of the system are described.

### 2.1 CCD cameras

The choice of the camera and sensor is crucial, and depends in large part on the desired features of the final system. Our system was designed as a preliminary research system that provides adequate image quality over a moderate field of view in order to evaluate stereoscopic algorithm approaches. On the camera side, the following criteria were considered: stability of the interior orientation (chip, focal length), the possibility of controlling all camera functions from a laptop computer, the maximal opening angle of usable lenses, the maximal exposure time (at least 20-30 seconds for optimal extraction of the star paths in the star calibration), performance of image storage and transfer (i.e. time delay until next image can be acquired), data format, power supply requirements and the camera price. On the sensor side, the spatial, spectral and radiometric resolution of the chip, as well as its dynamic range and noise characteristics, had to be considered. Table 2.1 shows an overview of the minimum and optimal requirements for the new camera system. For the prototype system described in this thesis, the minimum requirements are suffi-

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<thead>
<tr>
<th>Criteria</th>
<th>Minimum requirements</th>
<th>Optimal configuration</th>
</tr>
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<tbody>
<tr>
<td>Stability</td>
<td>Stable interior orientation</td>
<td>Stable interior orientation</td>
</tr>
<tr>
<td>Camera control</td>
<td>Important camera functions (e.g. shutter, exposure time)</td>
<td>All camera functions</td>
</tr>
<tr>
<td>Lens</td>
<td>Wide-angle (&gt; 100°)</td>
<td>Whole-sky</td>
</tr>
<tr>
<td>Max. exposure time</td>
<td>&gt; 20-30 s</td>
<td>&gt; 20-30 s</td>
</tr>
<tr>
<td>Image transfer performance</td>
<td>&lt; 60 s</td>
<td>&lt; 30 s</td>
</tr>
<tr>
<td>Price</td>
<td>&lt; $5'000</td>
<td>&lt; $5'000</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>&gt; 3.4 Mio</td>
<td>&gt; 6.0 Mio</td>
</tr>
<tr>
<td>Spectral range</td>
<td>VIS</td>
<td>VIS</td>
</tr>
<tr>
<td>Radiometric resolution</td>
<td>8-bit / channel</td>
<td>12-bit / channel</td>
</tr>
<tr>
<td>Noise characteristics</td>
<td>Low noise</td>
<td>Very low noise (e.g. cooled sensor)</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>70 dB</td>
<td>80-100 dB</td>
</tr>
</tbody>
</table>

Table 2.1: Minimal and optimal camera requirements for a cloud imaging system.
cient to reach the research goals with an acceptable accuracy and user comfort, while the optimal requirements should be clearly considered for an operational system.

The two major technologies that are currently used to manufacture imaging sensors are 1) Charge Coupled Device (CCD) and 2) Complementary Metal Oxide Semiconductor (CMOS) technologies. The main difference between a CCD and CMOS chip is the process of retrieving the values (i.e. accumulated charge) of each cell in the image (Blanc and Lang, 2001). Table 2.2 lists the strengths and weaknesses of a CMOS sensor in comparison to CCD sensors. In a CCD device, the charge is transported across the chip and read via a linear register located at the chip border. Depending on the CCD architecture type, the transfer into the linear register is done via vertical transfer registers (Interline Transfer and Field Interline Transfer CCD) or via a full frame transfer register (Frame transfer CCD). An analog-to-digital converter subsequently turns each pixel value from the linear register into a digital value. In a CMOS device, there are several transistors at each pixel, which amplify and move the charge directly. So, the CMOS approach is more flexible because each pixel can be read individually. The individual pixel readout of a CMOS sensor has the further advantage with respect to our application of eliminating blooming effects without the use of a sun occultor. A blooming effect is an overflow of charge from an oversaturated pixel to neighbouring pixels around the saturated pixel that is typically visible as either a vertical streak or white halo extending for several pixels (see Section 2.5.2). Nevertheless, a sun occultor would be necessary for a CMOS sensor to avoid stray light effects. Unfortunately, the noise of currently available CMOS sensors, used only without cooling so far, is very high. For our application, the larger noise compared to current CCD cameras would cause problems in cloud matching, especially for thinner clouds. Currently, no cooled CMOS systems are available on the camera market (Nicolas Blanc, personal communication); however, the planned Polar-CCi4 camera from VectorInternational (VectorInternational, 2002) might be pertinent to our application when it becomes available.

Evaluating CCD cameras showed that low cost cameras (< $2'000) cannot be used for our system as many necessary features are missing, like remote camera control, longer exposure times (at least 30 s), a wide-angle lens and geometric stability. Moreover, the planned time-to-market

| + Random access of region of interest |
| + Smart sensors and pixels (with added functionality) |
| + No blooming, no smearing |
| + Low power consumption (factor 1:10 vs. CCD) |
| + Size, weight |
| – Dark current (CCD: 2-50 pA/cm²; CMOS: 100-1000 pA/cm²) |
| – Fill factor (Frame Transfer CCD: 100 %; CMOS: 25-65%) |

Table 2.2: Strengths (+) and weaknesses(-) of CMOS vs. CCD image sensors.
of many sensors often gets delayed significantly. For example, the new low-cost astronomical
camera series of Apogee Inc. (Apogee, 2002) called LISÄÄ was announced for December 2000,
but it is still not available to date (August 2002). The LISÄÄ Megapixel Color camera would have
been a reasonable alternative from the group of cooled astronomical cameras to the uncooled
SLR cameras (Kodak DCS, Nikon D1, Fujifilm S1 Pro, etc.) at approximately the same price
($2'000 - $8'000). The characteristics of the newest SLR camera models (Kodak DCS Pro 14n,
Canon 1Ds, Fujifilm S2 Pro, etc.) improved mainly for the number of sensor elements (e.g. Kodak
DCS Pro 14n with 14 million pixels) and the speed of the data transfer interface (FireWire IEEE-
1394 vs. SCSI/USB).

In Cloudmap two Kodak DCS460c cameras were available for stereoscopic use. Due to time
constraints with the Mesoscale Alpine Programme (MAP) field campaign in autumn 1999, not all
necessary camera and sensor characteristics could be considered for this first prototype system.
For the Cloudmap2 prototype the Fujifilm S1 Pro camera was chosen after an extensive market
analysis. The characteristics of the Kodak DCS460 and the Fujifilm S1 Pro cameras are sum-
marized in Table 2.3. The main reason to switch cameras was the fact that the KODAK DCS460
camera was not internally stable, which was already shown in earlier tests (Shortis et al., 1998),
but which I did not anticipate having a considerable impact on this application. In fact, a movement
of the chip occurred during the MAP measurement campaign, which was possible because the
chip is only attached along one chip border using the so called “spring mounting” (see Section
2.1.1). A further disadvantage of the Kodak DCS460 is that the shutter release for longer expo-
sure times (> 30 s) is not controllable via the camera control software. This is problematic, as any

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Kodak DCS460</th>
<th>Fujifilm S1 Pro</th>
</tr>
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<tbody>
<tr>
<td>KAF-6300</td>
<td>Super CCD</td>
<td></td>
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<table>
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<tr>
<th>Number of sensor elements</th>
<th>3000 x 2036</th>
<th>2160 x 1544 (octagonal pixels)</th>
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<tbody>
<tr>
<td>3040 x 2016 (interpolated)</td>
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<td></td>
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<tr>
<th>CCD size</th>
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<th>23.3 x 15.6 mm</th>
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<thead>
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<th>Sensor element spacing</th>
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<th>0.0075 mm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Sensitivity (ISO)</th>
<th>80</th>
<th>320-1000</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Data transfer interface</th>
<th>SCSI</th>
<th>USB</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Price</th>
<th>$20'000</th>
<th>$3’000</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Spectral range</th>
<th>390 - 1050 nm</th>
<th>380 - 700 nm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Dark current</th>
<th>10 pA/cm² at 25°C</th>
<th>5-10 pA/cm² at 25°C *</th>
</tr>
</thead>
</table>

| Dynamic range | 75 dB | 70-75 dB *
|---------------|-------|-----------|

<table>
<thead>
<tr>
<th>Radiometric resolution</th>
<th>8-bit/ channel (raw)</th>
<th>8-bit/ channel (raw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-bit/ channel (interpolated)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Characteristics of the Kodak DCS460 and the Fujifilm S1 Pro cameras. *: exact figures
are not available from Fujifilm for dark current and dynamic range.
manual operations on the camera can affect the stability of the exterior orientation and should be avoided.

2.1.1 Kodak DCS460

The Kodak DCS460c is a digital still video sensor housed in a standard Nikon N90 SLR camera body. The color CCD chip (indicated by the “c” in “DCS460c”) is positioned in the film plane of the camera with the so-called “spring mounting” (Shortis et al., 1998) (Figure 2.1 top right). The images are either stored on the internal PCMCIA hard-drive or directly transferred to a computer via the SCSI interface. An investigation of the DCS460 camera for mapping purposes is described in Mason et al. (1997).

The Kodak DCS460c CCD array is a KAF-6300 with 3072 x 2048 pixels, each 9 x 9 μm² with a Bayer color filter (Bayer, 1976) (Figure 2.1 bottom right). In the KODAK image processing software the 6 rows and columns around the edge of the array are discarded. The RGB values (8- or 12-bit per color) of the remaining 3060 x 2036 pixels are calculated with the KODAK proprietary Active Interpolation algorithm from the original 8-bit red, green and blue filter values (Adams et al., 1998).

The dark current noise of this sensor is quite substantial (10 pA/cm² at 25°C) and significantly degrades the long-exposure-time night images that are used for exterior orientation with stars (see Section 2.4.2). Therefore, images with the lens cap closed were taken at various exposure times between 0.002 and 240 s for each camera to analyze the dark current noise. It was shown that the flat field is camera-dependent, spatially variable, temporally stable and increases with longer exposure times. Due to the strong temperature dependence of the dark current noise (about a
factor of 2 for a temperature increase of 5-10°C), these flat field images have to be retaken during every star calibration session to avoid large deviations in the magnitude of the noise because of changed temperature conditions.

2.1.2 Fujifilm S1 Pro

The first professional digital camera from Fujifilm, the FinePix S1 Pro, is based on the Nikon N60 camera body and has a 1.1 inch color CCD sensor. The camera uses a Nikon F lens mount. Possible shutter speed is from 30 to 1/2000 s. Images are either stored on a CompactFlash card in the camera or directly transferred to a computer via the USB interface. The successor model of the S1 Pro, the S2 Pro (available since April 2002), transfers images via a faster Firewire-IEEE1394 connection, which will improve the current download time of cloud images from about 40 s (full resolution) to approximately 20 s.

The Fujifilm S1 Pro CCD array is a SuperCCD (Figure 2.2) with 3.4 million octagonal pixels and a special color filter as described in Tamayama et al. (2000). In the proprietary Fujifilm processing software the octagonal color array counts are interpolated to 3040 x 2016 square pixels with a pixel size of 7.5 μm. The new CCD design attempts to increase sensitivity, dynamic range, signal-to-noise ratio and image quality. The 30 s night images show much less noise than the Kodak DCS460 images; stars can be extracted directly from the 30 s images without any previous flat field subtraction. To obtain exposure times of up to 150 s, the camera offers a feature of taking a sequence of up to five images without storage delay (temporal storage array) that can then be summed up and clipped above the maximum grey value by image processing software (see star paths in Section 2.4.2).

2.2 Camera hardware and software

For Cloudmap2, the simple MAP Kodak DCS460c prototype system described in Seiz and Balt-savias (2000a) was optimized by the use of a new camera (Fujifilm S1 Pro), improved camera
control software and a new camera housing, which includes heating and an automated sun oc-
cultor. Overall, the system was well-suited for the investigation of our cloud imager research
objectives and for providing validation data coincident with satellite images and input data for
cloud and NWP model case studies. Nevertheless, the system was still a research system and
not immune to the difficulties of an operational system (e.g. Shields et al. 1999). In this section
the hardware and software of the improved Cloudmap2 system are presented.

2.2.1 Description of the system

Each camera system consists of a color digital CCD camera, currently a Fujifilm S1 Pro, con-
nected via a USB interface to a laptop computer with precise time information from a GPS re-
ceiver or radio clock (Figure 2.3 right). The shutter release is controlled by self-developed camera
control software based on the commercial Fujifilm SDK library. The camera is protected within a
heated box (1-2° C above air temperature to avoid condensation on image sensor) that is mounted
on a tripod (Figure 2.3 left). Three levelling screws at the bottom of the camera housing allow pre-
cise horizontal adjustment of the camera image plane. Approximate adjustment of the camera
azimuth parallel to the baseline is done via a small telescope as the different cameras are always
within sight of each other. A more precise relative adjustment is then done by taking simultaneous
sample images with both cameras, overlaying the two images in an image processing software
and determining any residual rotation angle. Attached to the camera box is a moving sun occultor
device to prevent blooming effects caused by the sun. A Nikon 18 mm wide-angle lens with a
nominal viewing angle of 100° is used. If it starts to rain or snow, or if the camera is not used for a
long time, there is a remotely controlled cap which can be closed over the camera lens to protect it
against drops, dust, etc. (Figure 2.4). Just above the lens, there is a small opening through which a
stream of slightly heated air can be blown over the lens for cleaning. The camera system was
constructed at the Institute of Geodesy and Photogrammetry, ETH, based on an old MeteoSwiss
prototype (with an analog camera).

### 2.2.2 Camera control software

With the self-developed camera control software based on the Fujifilm SDK library, all camera functions can be controlled remotely. This is a great advantage over the Kodak DCS460 SDK, where only the shutter release function was remotely accessible and all of the other important functions for an automated cloud imager system, such as the exposure time, the aperture or the ISO setting, were not. In the Graphical User Interface (GUI) of the software (Figure 2.5) the start time, interval between images and number of images can be chosen, along with the exposure time, aperture and ISO sensitivity value. After acquisition, the most recent image is shown as a preview image on the screen as well as saved onto the laptop hard-disk. Saving an image takes up to 40 s for the highest image resolution (18 MB). For faster image acquisition with 30 s or higher sampling, one has to use a lower resolution image format to avoid time delays and hence loss of synchronization due to insufficient storage time. For star calibration images taken at night (see Section 2.4.2) a special “Night” function was created to allow five consecutive 30 s images without any delay between images. The Fujifilm S1 Pro camera allows for this possibility by a temporary on-camera storage of up to 5 images, which increases the theoretical maximum exposure time from 30 s to 150 s. So, star calibration with the Fujifilm S1 Pro is comparable to calibration of the Kodak DCS460, where star images of up to 4 min exposure time were used.
Next to the locations of the cameras, which were chosen as near as possible to other cloud-base height measurement instruments, the definition of the camera base length is the most important parameter in the geometric setup of the cameras. The choice of an appropriate base length for cloud mapping is difficult because of the wide height range of clouds (up to 15 km). There is a trade-off between an as-large-as-possible overlapping area, optimal matching conditions and an appropriate base-to-height ratio for the specific cloud situation, as will now be explained in detail.

The overlapping area of a stereo pair is calculated as (Kraus, 2000)

\[ \text{overlap} = \left(1 - \frac{bc}{xh}\right) \times 100\%, \]  

where \(b\) is the base length, \(x\) is the dimension of the sensor in the baseline direction, \(c\) is the focal length and \(h\) is the cloud height (above ground). So, as the base length decreases the overlapping area between the cameras increases. In addition, shorter base lengths (< 1 km) have the advantage that image matching is easier, faster and more reliable and many of the appearance difference problems reported in Allmen and Kegelmeyer (1996) are avoided.

But there is also an important argument for larger base lengths. The higher a cloud is situated the larger should be the base length due to the height accuracy \(s_z\) (Kraus, 2000):

\[ s_z = \frac{h}{c} \cdot \frac{h}{b} \cdot s_{px}, \]
where $\sigma_{\text{par}}$ is the parallax measurement accuracy. For an operational application of a stereo cloud mapping system, the use of a dynamic base between the two cameras with respect to the actual cloud height range through camera tilting and change of focal length, or the use of more than two cameras with different base lengths, as shown in our new setup at Zürich-Kloten, should be considered.

The first data acquisition took place during the Special Observation Period (SOP) of the Mesoscale Alpine Programme (MAP) in autumn 1999. The MAP is an ongoing international research initiative devoted to the study of atmospheric and hydrological processes over mountainous terrain. It aims towards expanding our knowledge of weather and climate over complex topography (MAP, 2002). The SOP lasted from September 7 to November 15, 1999. The SOP measurements were focused on three target areas: “Lago Maggiore” (CH/I), “Rhine Valley” (CH) and “Brennerpass/ Wipp Valley” (A). For “Föhn” events North of the Alps (Rhine Valley, Brennerpass) or heavy precipitation events South of the Alps (Lago Maggiore), Intensive Observation Periods (IOP) of 2-5 days were defined.

Our two cameras were situated at Mels within the target area “Rhine Valley”, Switzerland (Figure 2.6) and were separated by 850 m horizontally. The two locations were visible from each other and the baseline direction was parallel to the valley direction from NW to SE (Figure 2.6). For the MAP setup with $b = 850$ m, $c = 18$ mm and $x = 27.54$ mm, camera overlap starts at 560 m above ground level (AGL); at 3.5 km the overlap area is 84% and at 10 km 95%. With an assumed parallax measurement accuracy of 1 pixel ($= 9 \mu m$) and cloud heights of 3.5 km and 10 km AGL, we have height accuracies of 7.2 m and 58 m, respectively.

The new Cloudmap2 measurements since September 2001 are done at the MeteoSwiss station at Zürich-Kloten Airport (Figure 2.7). Two of the three camera locations were dictated by the available logistics: camera 1 on the roof of the MeteoSwiss observation station “Oberglatt” and camera 2 at the ANETZ measurement site, with a horizontal spacing of 550 m. The third location
near the observation station “Oberglatt”, with a short base length of 80 m and orthogonal to the other base direction, was set up temporarily to test the use of a three-camera system.

For the Zürich-Kloten setup of cameras 1 and 2 with $b = 550$ m, $c = 18$ mm and $x = 22.8$ mm, the camera overlap starts at 430 m AGL; at 3.5 km the overlap area is 88% and at 10 km 96%. With an assumed parallax measurement accuracy of 1 pixel (= 7.5 $\mu$m) and cloud heights of 3.5 km and 10 km AGL, we have height accuracies of 9.3 m and 76 m, respectively.

### 2.4 Geometric calibration

The mathematical model for the determination of the three-dimensional object coordinates $(X, Y, Z)$ is based on the collinearity equations with corrections $(\Delta x, \Delta y)$ for systematic errors (Figure 2.8):

$$
\begin{align*}
    x &= x_p - c \cdot \frac{r_{11} (X - X_0) + r_{21} (Y - Y_0) + r_{31} (Z - Z_0)}{r_{13} (X - X_0) + r_{23} (Y - Y_0) + r_{33} (Z - Z_0)} + \Delta x \\
    y &= y_p - c \cdot \frac{r_{12} (X - X_0) + r_{22} (Y - Y_0) + r_{32} (Z - Z_0)}{r_{13} (X - X_0) + r_{23} (Y - Y_0) + r_{33} (Z - Z_0)} + \Delta y,
\end{align*}
$$

(2.3)

where $(x, y)$ are the image coordinates of the object point, $(x_p, y_p)$ are the image coordinates of the principal point, $c$ is the focal length and $r_{ij}$ are the elements of rotation matrix $R$ (see Equation 2.6). The transformation between the image coordinates $(x, y)$ in the right-handed image coordinate system with its origin at the principal point and the pixel coordinates $(x', y')$ in the left-handed pixel coordinate system with its origin at the left topmost pixel is illustrated in Figure 2.8 and defined as

$$
\begin{align*}
    x &= (x' - x'_p) \ast p_{sx} + x_p = (x' - x'_M) \ast p_{sx} \\
    y &= (y' - y'_p) \ast p_{sy} + y_p = (y'_M - y'_p) \ast p_{sy},
\end{align*}
$$

(2.4)

where $(x'_p, y'_p)$ is the location of the principal point in pixel coordinates and $p_{sx}, p_{sy}$ are the pixel spacing in $x$ and $y$. The most significant systematic errors (focal length, principle point offset, lens distortion and non-orthogonality of chip axes) are modelled with ten additional parameters.
after Brown (1971): three parameters for interior orientation offsets (focal length offset \( dx_p \) and principal point coordinate offsets \( dy_p \)), five parameters modelling radial and decentering lens distortion (radial coefficients \( k_1, k_2, k_3 \); decentering coefficients \( p_1, p_2 \)) and two parameters for a differential scale factor \( a_1 \) and a correction \( a_2 \) for the non-orthogonality of the image coordinate axes (Beyer, 1992):

\[
\begin{align*}
\Delta x &= dx_p - \frac{\overline{y}}{c}dc - \overline{x}a_1 + \overline{y}a_2 + \overline{y}^2 k_1 + \overline{y}r^4 k_2 + \overline{y}r^6 k_3 + (r^2 + 2\overline{y}^2)p_1 + 2\overline{y}rp_2, \\
\Delta y &= dy_p - \frac{\overline{x}}{c}dc + \overline{x}a_2 + \overline{x}r^2 k_1 + \overline{x}r^4 k_2 + \overline{x}r^6 k_3 + 2\overline{x}rp_1 + (r^2 + 2\overline{x}^2)p_2,
\end{align*}
\]

where \( \overline{x} = x - x_p, \overline{y} = y - y_p \) and \( r = \sqrt{\overline{x}^2 + \overline{y}^2} \).

The exterior orientation elements of the two or more cameras consist of the projection center \( (X_0, Y_0, Z_0) \) and the rotation matrix \( \mathbf{R} \) with the rotation angles \( \omega, \phi, \kappa \):

\[
\mathbf{R} = \begin{pmatrix}
\cos \phi \cos \kappa & -\cos \phi \sin \kappa & \sin \phi \\
\cos \omega \sin \kappa + \sin \omega \sin \phi \cos \kappa & \cos \omega \cos \kappa - \sin \omega \sin \phi \sin \kappa & -\sin \omega \cos \phi \\
\sin \omega \sin \kappa - \cos \omega \sin \phi \cos \kappa & \sin \omega \cos \kappa + \cos \omega \sin \phi \sin \kappa & \cos \omega \cos \phi
\end{pmatrix}.
\]

The following two subsections describe how the six parameters of the exterior orientation \( (X_0, Y_0, Z_0, \omega, \phi, \kappa) \) and the ten parameters of the interior orientation \( (c, x_p, y_p, k_1, k_2, k_3, p_1, p_2, a_1, a_2) \) are measured and calculated for each camera system.

### 2.4.1 Interior orientation

The interior orientation parameters are determined with a close-range photogrammetric reference field at our Institute of 4.2 x 2.0 x 1.2 m with 77 signalized and 20 coded points (Figure 2.9). The
20 coded points (white coded symbol on black background) can be identified automatically by template matching in the calibration process without any approximate value (Niederoest, 1996), while the 77 signalized points (black points on white background) can only be identified by template matching with the use of a first rough orientation from the 20 coded points. For each camera 15 images were taken, consisting of 5 camera stations (left high, left low, center, right high, right low) at three different roll angles (-90°, 0°, +90°).

The camera model parameters were calculated simultaneously with camera orientation data and 3-D object point coordinates, employing a self-calibrating bundle adjustment. Ten additional parameters were used to model systematic errors as described in Equation 2.5. In the bundle adjustment results the differential scale factor $a_1$, the non-orthogonality factor $a_2$ and the higher order lens distortion coefficients $k_3$ and $p_2$ proved to be insignificant. The interior orientation results for the two Kodak DCS460 cameras taken before the MAP campaign are presented in Table 2.4, while Figure 2.10 shows the quite substantial radial and decentering distortion of the two high-quality 18 mm wide-angle Nikon lenses. The large distortions towards the image borders and the significant differences between the two lenses illustrate that each lens has to be calibrated independently. A second testfield calibration of both cameras made after the MAP measurement.

<table>
<thead>
<tr>
<th>Camera</th>
<th>$c$ [mm]</th>
<th>$x_p$ [mm]</th>
<th>$y_p$ [mm]</th>
<th>$k_1$ [mm$^{-2}$]</th>
<th>$k_2$ [mm$^{-4}$]</th>
<th>$p_1$ [mm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera 1</td>
<td>18.641</td>
<td>0.3053</td>
<td>-0.2690</td>
<td>-2.983e-4</td>
<td>5.940e-7</td>
<td>2.7e-5</td>
</tr>
<tr>
<td></td>
<td>± 1.3e-3</td>
<td>± 6.2e-4</td>
<td>± 1.8e-3</td>
<td>± 7.6e-7</td>
<td>± 4.6e-9</td>
<td>± 1.6e-6</td>
</tr>
<tr>
<td>Camera 2</td>
<td>18.516</td>
<td>0.2796</td>
<td>0.0003</td>
<td>-2.370e-4</td>
<td>5.223e-7</td>
<td>-7.4e-5</td>
</tr>
<tr>
<td></td>
<td>± 1.1e-3</td>
<td>± 4.7e-4</td>
<td>± 1.6e-3</td>
<td>± 7.9e-7</td>
<td>± 5.2e-9</td>
<td>± 1.3e-6</td>
</tr>
</tbody>
</table>

Table 2.4: Interior orientation parameters and their standard deviation as determined from the testfield calibration.
campaign showed an instability of the principal point of both cameras of up to 0.15mm in x- and 0.05mm in y-direction which is caused by the insufficient fixing of the chip, as described in Section 2.1.

2.4.2 Exterior orientation

The exterior orientation of all cameras has to be determined at the measurement locations. As the cameras are horizontally adjusted and the field of view only includes clouds and sky, the traditional methods with ground control points could not be used. Instead of ground control points, "sky control points" had to be measured. In the MAP campaign two independent sets of sky control points were established: 1) during daylight, an airplane equipped with differential GPS (DGPS) and 2) during clear nights, stars visible in long exposure night images.

2.4.2.1 Airplane

To get artificial sky control points during daylight, a previously calculated flight pattern was flown by the KingAir of the Swiss Army. The flight lines were parallel to the baseline of the two cameras. The highest flight line was 4000 m AGL, while the lowest flight line was at 1000 m AGL. The flight lines were calculated with the given camera orientations to be along the left and right border of the images (4000 m and 2000 m AGL) and through the image center (1000 m AGL). Given the mean velocity of the airplane of 100 m/s and an image storage delay of 8s, the plane on its lowest flight line was visible in 1-2 images and in 5-8 images on its highest flight level. The DGPS antenna of the airplane was then manually measured in every image. From the exact acquisition time of the image, the 3D coordinates of the point could be determined from the differential GPS calculations and used as a control point. With a bundle adjustment with fixed interior orientation parameters
from the testfield calibration and station coordinates from static GPS, the orientation angles were estimated together for both cameras. The image residuals show an accuracy of approximately 3 pixels across-track, consistent with the difficulties of identifying the location of the antenna in the images, especially due to the oblique viewing angle for the higher flight lines (Figure 2.11), but an accuracy of 10-15 pixels along-track that is caused by errors in the acquisition time. At a mean KingAir velocity of 100 m/s, 10 pixels correspond to a time error of about 100 ms at the mean flight height, which is about the accuracy of the laptop computer time. The stability of the angles in the bundle adjustment was improved with tie points on clouds near the edges of the image.

2.4.2.2 Stars

As an alternative method, star images were used to determine the exterior orientation angles. This second method is more realistic for an operational sky imager network where recalibration of the orientation angles is necessary at regular time intervals. The night sky calibration images with long exposure times were taken during clear nights. When the exposure time was longer than about one minute, the paths of the brightest stars could be seen between the noise (Figure 2.12). Although the noise represents a sum of dark current noise and sky background (atmospheric light scatter, etc.), it can in this case of low sky background be modelled as a dark current noise image alone, taken with a similar exposure time. The raw 8-bit color array values, which are fortunately accessible from the KODAK camera, were used directly, before any color interpolation. The star path images were then further processed by specialized software (Ploner, 1996) to identify the stars corresponding to the Position and Proper Motion (PPM) star catalog and to calculate the orientation angles of each camera.

The optimal exposure time is based on two factors: the detectability of the linear star track within the noise pattern, which increases with increasing exposure time, and the linear form of the star path, which decreases with increasing exposure time. The star path is taken to be a straight line by the processing software which finds the central point of each path by a centroid operator. Only these central points are used in the calculations. The accuracy of the calculated photogrammetric angles $\omega$, $\phi$ and $\kappa$ from the star images is $\pm 40^\circ$. Using the same software package, the interior orientation parameters (same 10 parameter set as described in Equation 2.5) of the cameras can additionally be estimated, which is promising for longer measurement periods when the interior
orientation of a theoretically stable camera might eventually change over time. For example, the star calibration procedure helped to identify the chip movements of the Kodak DCS460 cameras during the MAP campaign, as well as to detect a change in the focal length of camera 1 during test measurements at Zürich-Kloten that was caused by inadequate anchoring of the AF lens ring adapter.

In Cloudmap2 only the second method (i.e. star calibration) was applied as it is logistically much easier and is, as said, more realistic for an operational imager network where recalibration of the orientation angles is necessary at regular time intervals. As the dark current noise of the Fujifilm S1 Pro camera is much lower than for the Kodak DCS460 camera, star detection is possible in the 30 s exposure images in most cases. At locations with strong light contamination (e.g. near highways) or at times with strong moon light, one has to work with the 60 s or longer exposure times so that the star paths are clearly detectable as linear features within the sky background noise (Figure 2.13). Longer exposure images (> 30 s) can be obtained with the Fujifilm S1 Pro by summing single 30 s images with no (or minimal) time delay between the images. Our control software offers a special night function for this task, as described in Section 2.2.2.

The coordinates $X_0$, $Y_0$ and $Z_0$ of the camera stations were measured with GPS during the MAP campaign, as well as at Zürich-Kloten, with a relative accuracy (i.e. distance between the cameras) of 5-10 cm and an absolute accuracy of about the same magnitude of 5-10 cm.
2.5 Environmental influence factors

The quality of outdoor ground-based cloud images is not only determined by the camera characteristics, the interior orientation and the exterior orientation. Additionally, the distortion of the images is influenced by atmospheric refraction and the image quality is affected by blooming. In the following paragraphs these factors and their influence on the cloud measurements are briefly described.

2.5.1 Atmospheric refraction

Atmospheric refraction is the result of changes in density of the atmosphere that cause light to follow a curved path instead of a straight line. The angle $\alpha$ between the theoretical straight line of sight and the tangent to the actual light path at the camera is a function of altitude, direction of the ray and atmospheric conditions along the path. Through the effect of refraction, the true image point is displaced radially by $\delta r$ (Figure 2.15).

Several methods have been proposed for the correction of the effects of atmospheric refraction (Manual of Photogrammetry, 1980; Albertz and Kreiling, 1989). For vertical and near-vertical images, the following simple method is often used:

$$\delta r = K \left( r + \frac{r^3}{f^2} \right),$$

where $r$ is the radial distance of the measured point from the image center [mm], $f$ is the focal length [mm] and $K$ is an atmospheric constant usually determined from the Standard Atmosphere. The following expression for $K$ from Saastamoinen (Manual of Photogrammetry, 1980) is widely used in aerial photogrammetry:

$$K = 13(h_{\text{cloud}} - h_{\text{camera}}) \left[ 1 - 0.02(2h_{\text{cloud}} + h_{\text{camera}}) \right] \times 10^{-6},$$

where $h_{\text{cloud}}$ is the height of cloud base and $h_{\text{camera}}$ is the camera height, both in km above sea-level (ASL). With a camera height $h_{\text{camera}}$ of 0.5 km, a maximal cloud height $h_{\text{cloud}}$ of 12 km, focal length $f$ of 18.5 mm and a maximum radial distance on the CCD chip of 13.7 mm, we calculate an
atmospheric constant \( K \) of 0.000076, implying a maximum radial distortion due to atmospheric refraction of \( \delta r = 0.0016 \) mm. With a pixel size of 0.009 mm for the Kodak DCS460 and a pixel size of 0.0075 mm for the Fujifilm S1 Pro camera, the radial distortion \( \delta r \) is much less than one pixel and does not significantly influence the cloud-base height retrieval.

### 2.5.2 Influences of sunlight

Each pixel on a digital camera sensor has a limit on how much charge it can store. Blooming, or streaking, is the name given to an overflow of charge from an oversaturated pixel to its neighbors on the sensor. The advantage of a CMOS sensor is that only one pixel is “destroyed”, while for a CCD sensor without an anti-blooming gate, the overflow can affect the whole sensor column (Figure 2.16). The best way to avoid blooming effects in images is the use of a sun occultor, which is readily available today for many measurement instruments. A sun occultor is furthermore a good tool to avoid stray light effects in the images. Another possibility against blooming is to use a CCD camera with a so-called “anti-blooming gate”, but these sensors are in general less sensitive and stray light effects cannot be completely avoided this way.

Measuring large light differences and avoiding saturation can be a problem in cloud imaging, so that a chip with a large dynamic range is required. CMOS sensors thereby offer the possibility to implement a logarithmic instead of a linear response curve (Ricquier and Dierickx, 1992). The

---

**Figure 2.15:** Illustration of atmospheric refraction when acquiring ground-based cloud images.
FUGA sensor (Vector International, 2002) has such a logarithmic response curve, which is similar to the response of the human eye and allows to cover a dynamic range of up to 120 dB. The Swiss Center for Electronics and Microtechnology (CSEM) patented another logarithmic CMOS chip concept recently, the so-called LinLog™ technique (Nicolas Blanc, personal communication). Darker image parts are imaged with a linear response function while a logarithmic response function is used for the brighter image parts.
Chapter 3

Cloud-adapted matching algorithm

To calculate cloud-base height (CBH) and cloud-top height (CTH) automatically, different image processing algorithms, including image matching, have to be applied to the stereo images. At our Institute many such algorithms have been developed over the last 20 years and have been employed in matching various objects. The approach within Cloudmap was to test existing methods and to adapt them when necessary to reduce special problems encountered with clouds. Such problems include: the different appearance of clouds as the view angle and illumination conditions change, semitransparent surfaces (e.g. with cirrus clouds), large discontinuities in object space between surfaces that appear to be adjacent in the image (e.g. clouds and sky, multilayered clouds), surface discontinuities within one cloud, lack of texture, saturation and lack of clear cloud boundary definition (Figure 3.1). The main focus of Cloudmap was on achieving a high success rate, accuracy and reliability, while not emphasizing processing speed. Of course, processing speed is clearly of importance if a system is to be used operationally in near-realtime.

An overview of the processing steps applied to the ground- and satellite-based cloud images, which are described in detail in the following sections, is illustrated in Figure 3.2. The same

Figure 3.1: Illustration of problems encountered with clouds. Left: semitransparent surfaces, lack of texture; right: large discontinuities in object space with multiple cloud layers, lack of texture, saturation.
algorithms can also be used for derivation of cloud motion by matching corresponding features in image sequences. Although our approach is mostly applied to single stereo pairs, the use of image sequences can simplify many aspects of the height calculations, including derivation of approximate values, quality control or image segmentation.

3.1 Preprocessing

For the ground-based images 8-bit greyscale images were used. The greyscale images were either generated from the red channel for the Kodak DCS460 images or from the full RGB images with RGB-to-greyscale conversion (e.g. default Adobe Photoshop RGB-to-greyscale conversion, where the converted pixels represent the luminosity of the original pixels) for the Fujifilm S1 Pro images. The dark current was not subtracted from the cloud images, as it was done for the star images, because of the small exposure times of 1/1000 - 1/250 s for the Kodak DCS460 and 1/2000 - 1/1000 s for the Fujifilm S1 Pro. The satellite-based images were also reduced to 8-bit, where necessary, with linear stretching between the minimum and maximum values. To avoid the influence of a few outlying values, the minimum and maximum values were defined by cutting 0.5% of the values on both sides of the histogram. The specific data characteristics and processing of the satellite images before entering the cloud-adapted matching algorithm are described in Sections 5.1.1 (ATSR2), 5.1.2 (MISR) and 5.1.3 (ASTER).

To facilitate matching, a Wallis filter (Wallis, 1976; Baltsavias, 1991) was used for radiometric equalization of the images and contrast enhancement. The Wallis filter is an adaptive, local filter, which has been extensively used at our Institute in image preprocessing for matching (e.g. Baltsavias, 1991; Baltsavias et al., 1996). The filter is defined with the objective of forcing the
mean and standard deviation of an image to given target values. The filtered image is calculated as

\[ img_{\text{new}}(x, y) = img(x, y)r_1 + r_0, \]  

(3.1)

where

\[ r_1 = c \frac{s_f}{cs_g + (1 - c)s_f}, \]

\[ r_0 = bm_f + (1 - b - r_1)m_g, \]  

(3.2)

\((m_g, s_g)\) are the original mean and standard deviation of each block, \((m_f, s_f)\) are the target mean and standard deviation for every block, \(b\) \((0 \leq b \leq 1)\) is the brightness forcing constant and \(c\) \((0 \leq c \leq 1)\) is the contrast expansion constant.

The filter works as follows. First, the image is divided into blocks with dimensions of the so-called “filter size” \(B\) and according to the defined “distance between block centers” \(d\). Then, the parameters \(r_0\) and \(r_1\) are computed in each block. Finally, each pixel of the original image is transformed with \(r_0'\) and \(r_1'\) which were bilinearly interpolated from the \(r_0, r_1\) values of the 4 neighbouring block centers. The contrast enhancing effect of the Wallis filter on ground- and satellite-based images is illustrated in Figures 3.3 and 3.4. In areas with the same grey values (e.g. saturated areas) the filter cannot create any texture, but in areas with weak texture patterns the filtering strongly enhances the texture so that the images are optimized for matching. According to the chosen block size \(B\), different cloud structures are particularly enhanced, which is especially interesting for satellite images covering large areas with various cloud systems (e.g. Meteosat).

By preprocessing the images with a Wallis filter, radiometric corrections during matching are no longer necessary if the patch size in the matching is about the same size as the block size of the Wallis filter. All regions of the images are forced to have the same grey level mean and standard deviation and the grey level statistics will be the same for the patches and the template (Baltsavias, 1991).
Feature extraction is used to extract important image information, i.e. to suppress redundant information or neglect information which is not useful in subsequent processing steps (Fuchs and Heuel, 1998). The following sections will concentrate on “geometric features” like points, lines or regions, which refer to significant structures in the image. They can be clearly distinguished from higher level processes (according to the classification of Förstner 1991) like “structural features” (i.e. aggregates of geometric features like nodes, polygons, etc.) or “semantic features” (i.e. features carrying thematic information). In our application points and edges are directly used for matching while regions (i.e. cloud mask) are so far only taken as auxiliary information to thin out and reduce the point set to cloud points only. For completeness, region extraction for possible subsequent region matching is also shortly described in Section 3.2.3.2.

3.2 Feature extraction

Feature extraction is used to extract important image information, i.e. to suppress redundant information or neglect information which is not useful in subsequent processing steps (Fuchs and Heuel, 1998). The following sections will concentrate on “geometric features” like points, lines or regions, which refer to significant structures in the image. They can be clearly distinguished from higher level processes (according to the classification of Förstner 1991) like “structural features” (i.e. aggregates of geometric features like nodes, polygons, etc.) or “semantic features” (i.e. features carrying thematic information). In our application points and edges are directly used for matching while regions (i.e. cloud mask) are so far only taken as auxiliary information to thin out and reduce the point set to cloud points only. For completeness, region extraction for possible subsequent region matching is also shortly described in Section 3.2.3.2.

3.2.1 Points

Two different interest operators were used for point extraction, the Förstner operator (Förstner and Gülch, 1987) and the Harris operator (Harris and Stephens, 1988). Both have been extensively used in photogrammetry and computer vision. A comparison of the performance of various interest operators, including the Förstner and Harris operators, for different objects is described in Schmid et al. (1998).

3.2.1.1 Förstner operator

The Förstner operator extracts corner points, center points of circularly symmetric features and edge points. A corner or center point is selected if its window grey level signal ellipse is small and
circular based on two thresholds, while an edge point is detected if its signal ellipse is extended in the edge direction (Figure 3.5). Points within the textureless, or noisy, sky background have large, approximately circular signal ellipses and are not extracted.

The operator works in two steps. First, a $2 \times 2$ normal matrix $N$ is calculated for all image points using sums of the second grey level gradients $g_x^2$, $g_{xy}$ and $g_y^2$ within the operator window:

$$ N = \begin{pmatrix} \sum g_x^2 & \sum g_{xy} \\ \sum g_{xy} & \sum g_y^2 \end{pmatrix} $$

(3.3)

The gradients are computed by convolution of the image with a Sobel mask ($[1 0 -1, 2 0 -2, 1 0 -1]$ for x-gradients, $[1 2 1, 0 0 0, -1 -2 -1]$ for y-gradients). The operator window is usually chosen as 5 x 5 or 7 x 7 pixels. The normal matrix $N$ is called a texture descriptor and shows the direction and intensity of the local texture within the operator window. The direction of the local texture is given as

$$ \phi = \frac{1}{2} \arctan \left( \frac{4g_{xy}}{g_x^2 - g_y^2} \right) $$

(3.4)

In the second step, the weight $w$, which relates to the size of the error ellipse, and the roundness $q$, which is a measure of the shape of the signal ellipse, are computed:

$$ w(x, y) = \frac{\det N}{\text{tr}^2 N} $$

(3.5)

and

$$ q(x, y) = \frac{4 \det N}{\text{tr}^3 N} $$

(3.6)

Points with a weight $w$ above a threshold $w_{\text{min}}$ and with a roundness $q$ greater than a threshold $q_{\text{min}}$ are kept. Edge points are kept if their trace is above a threshold $\text{tr}_{\text{min}}$ and their roundness $q$ is below a second threshold $q_{\text{max}}$. Optionally, non-maxima suppression is applied to the points and thinning to the edges. Non-maxima suppression means that only the most significant point within a local neighborhood is kept. Thinning of the edges is a non-maxima suppression perpendicular to the edge direction. Finally, points are exactly localized using an estimation model for
the approximation of their sub-pixel position and each point is further classified as a corner point, a center of a circular area or generally good texture.

Within Cloudmap, a new version of the Förstner operator was developed and implemented. First, noise reduction by a Gaussian filter is optionally applied before the gradient derivation. Since a user may find it difficult to provide directly the thresholds $w_{\text{min}}$ and $t_{r_{\text{min}}}$ for the weight and trace without a lot of experience, as these values are dependent on the mask size and image content, the new implementation allows the minimum and maximum difference in grey values of adjacent pixels to be entered manually and the weight and trace thresholds are then computed automatically.

The point extraction with the Förstner operator for an altocumulus situation is illustrated in Figure 3.6. To avoid local image artifacts, like part of the sun occultor or dust particles on the lens, the extracted points are thinned using additional information. One approach to thinning the points is the use of a cloud mask, if available (see Section 3.2.3). The signal ellipse (i.e. axis direction, size and shape), which is the base of the Förstner operator, also gives some important local characteristics which can subsequently be used for area-based matching, for example to adjust the patch size and shape accordingly.

3.2.1.2 Harris operator

The Harris operator, which is also known as the Plessey feature point detector, is built on ideas similar to the Moravec interest operator (Moravec, 1977), except that local autocorrelation is estimated from first order image derivatives. The variation of the autocorrelation over different orientations is found by calculating functions related to the principle curvatures of the local autocorrelation. As with the Förstner operator, the normal matrix $\mathbf{N}$ is calculated first within a $5 \times 5$ window, but with different masks for the gradient calculation. The original Harris implementation from Harris and Stephens (1988) convolves the image with the mask $[-2 -1 0 1 2]$, while an improved version of Harris from INRIA (Schmid et al., 1998) works with derivatives of the Gaussian function. The interest parameter of the Harris operator is the so-called “cornerness” $c$:

$$c = \det \mathbf{N} - k \cdot t^2 \mathbf{N}. \quad (3.7)$$
The parameter \( k \), called the “scale”, is set by default to 0.04. Corners are then defined as local maxima in the cornerness function. To avoid points due to noise, the images can optionally be smoothed with a Gaussian filter before the calculation of the gradients.

As a general conclusion to point extraction, both the Förstner and Harris operators have to use dynamic thresholds (i.e. that are variable within the image) as results of the operators can be very different in various cloud regions. Such an adaptive method is contained in the implementation of both operators. Concerning the performance of the two point operators, no significant differences in the point distributions for various cloud types were found. However, the Förstner operator was often preferred for the processing of the ground-based images as it is able to detect points along selected edge directions which is useful as point selection for constrained matching (see Section 3.3.1.1).

### 3.2.2 Edges

The most widely used edge extraction algorithm is the Canny method, described in Canny (1986). The design of the Canny edge detector is concentrated on an ideal step edge, represented as a Sign function in one dimension that is corrupted by a Gaussian noise process. While this model ignores some aspects of reality, it does represent to good approximation the effects of sensor noise, sampling and quantization. The algorithm consists of four steps: image smoothing with a Gaussian filter with sigma \( \sigma \); differentiation with a Gaussian mask (same \( \sigma \)); non-maxima...
suppression; and edge thresholding (also called “hysteresis”).

Application of the Canny operator and transformation of the results into straight lines is based on
the work of Henricsson (1996). The results of applying our Canny operator (including transfor-
mation into straight lines) to a stereo pair with clouds are presented in Figure 3.7. The extracted
edges are amazingly similar in the two images, which is promising for a subsequent matching
process that attempts to find as many corresponding edges as possible between the two views.
Several attributes of the extracted straight lines can be used in subsequent feature-based, or
structural, matching, such as start and end points, length of line in pixels, angle with x-axis and
mean grey values on both sides of the line.

3.2.3 Regions

Regions are image areas that fulfill a certain similarity criterion. Such a similarity, or homogeneity,
criterion can be, for example, the intensity value of an image pixel or some texture properties in
the area surrounding a pixel. Region extraction divides an image into a number of subregions,
sometimes called “blobs”. One can distinguish between “incomplete segmentation”, where the
image is divided into homogeneous and inhomogeneous areas and the inhomogeneous areas,
the so-called “background”, is subsequently not considered in the following processing steps, and
“complete segmentation”, where the image is completely divided into regions according to the
similarity criterion.

Two types of region extraction are described in the following, cloud classification/masking and re-
gion extraction from quadrature filter results. Both methods are, in the end, incomplete segmen-
tations, although the cloud mask can be interpreted as a complete segmentation of the image. In
the first method non-cloud regions are treated as background, while in the second method noisy
regions are considered as background. According to the overview of region extraction techniques
given in Fuchs and Heuel (1998), both are classified as “threshold techniques”, compared to other
techniques like region growing, region merging or a split-and-merge approach.

3.2.3.1 Cloud masking

The most common region segmentation of both ground- and satellite-based images is the deriva-
tion of a cloud mask and a cloud classification of the cloudy parts. In our application a cloud
mask is helpful for filtering out points detected in the background noise of the sky before the
matching and for segmentation and visualization, while a cloud classification is more useful for
the end-users in the forecast office. We will concentrate on cloud masks only in the following
discussion.

Most cloud mask algorithms for ground-based sky camera systems work with the red/blue ratio
and a dynamic threshold (look-up table) that is adapted according to the camera location and
date/time of image acquisition (Janet Shields, personal communication). Our approach to derive
a cloud mask uses an image sequence and assumes that the radiance values within non-cloud parts are relatively stable during short time intervals while the values within clouds are constantly changing because of cloud motion. The results of the sequence-based cloud mask are shown in Figure 3.8. From the visual impression, most of the cloud pixels are correctly classified by the cloud mask algorithm. Wrongly classified pixels are mainly visible within the thinner clouds at the bottom left border and within the cloud object at the top of the image. In general, the approach has problems within larger cloud objects where pixel values may appear stable over short image sequences or for stable, slow moving clouds, but it can provide useful additional information for more accurate cloud mask estimation methods.

Many cloud classification and cloud mask algorithms exist for satellite-based data. For the ATSR2 images we implemented an algorithm based on the APOLLO scheme (Saunders and Kriebel, 1989), while for the MISR images the operational NASA JPL Level 2 product includes a cloud classification which we could use directly (Diner et al., 1999a). The three cloud tests based on the APOLLO scheme are applied to the ATSR2 data to separate cloud, land and mixed pixels: 1) 0.87 \(\text{\(\mu m\)} /11.0 \text{\(\mu m\)}\) ratio test, 2) 11.0 \(\text{\(\mu m\)}-3.7 \text{\(\mu m\)}\) difference test and 3) 3.7 \(\text{\(\mu m\)}-12.0 \text{\(\mu m\)}\) difference test. If a pixel passed all tests, it was classified as cloudy; if none of the tests were satisfied, the pixel was marked as land; all other pixels were classified as mixed. An extensive evaluation of the application of each of the APOLLO cloud tests to ATSR2 data is described in Zavody et al. (2000). In our study, we did not further evaluate the cloud test performance as the derived cloud mask was only used as auxiliary information to reduce the matching points to cloud points.

### 3.2.3.2 Quadrature filter

The analysis of local orientation and phase by a so-called “quadrature filter” offers another preprocessing possibility for the extraction of a number of homogeneous regions with respect to orientation and phase (incomplete segmentation). A quadrature filter is a complex two-dimensional filter whose real part is related to its imaginary part via a Hilbert transform along a particular axis.
through the origin. The details of quadrature filter methods are given in Granlund and Knutsson (1995).

We used an implementation of Boerlin (2000). The algorithm applies four different directional filters \(0^\circ, 45^\circ, 90^\circ, 135^\circ\) on the images. From the resulting real and imaginary images the composite color representation (HLS), as shown in Figure 3.9, can be derived, with the orientation angle as the H value, the magnitude as brightness value L and S set to 1.0:

\[
\text{magnitude} = \sqrt{\text{real}^2 + \text{imag}^2},
\]

\[
\text{angle} = \arctan \left( \frac{\text{imag}}{\text{real}} \right),
\]

\[
H = \text{angle},
\]

\[
L = \frac{\text{magnitude} - \min(\text{magnitude})}{\max(\text{magnitude}) - \min(\text{magnitude})},
\]

\[
S = 1.0.
\]

Similar to edge extraction, a potential region extraction based on the quadrature filter values magnitude/angle or H/L/S would be useful for our task if the extracted regions from the two images have similar characteristics. For the example stereo pair shown in Figure 3.9, this would probably be true in most parts of the image, depending of course on the applied algorithm to actually extract the region features. For the subsequent region matching, a number of attributes of the extracted
regions can be used. The following list summarizes the attributes that could be compared in a region-based matching algorithm, divided into geometric and radiometric criteria:

- **Geometry:** area, perimeter, width/height (rectangular box), centroid point
- **Radiometry:** gray values (average, standard deviation), RGB values.

### 3.3 Matching

Matching is defined as the establishment of the correspondence between various data sets. Problems in solving this task are also referred to as the correspondence problem. Matching is required in many processing steps in photogrammetry and remote sensing, like template matching for camera calibration, matching of tie points for georectification, digital terrain model (DTM) generation, etc.. Despite a large number of research studies on matching (e.g. Baltsavias 1991; Heipke 1996), the task still remains challenging, especially within a new application with different characteristics for the objects to be matched.

Categorization of matching algorithms is generally done according to the matching primitives that are used in the actual matching step: area-based matching, feature-based matching and structural, or relational, matching. In the following subsections these three matching categories are described, along with the matching methods that we finally applied to the cloud images. As one can recognize, not every method clearly belongs to a single category; there are also “hybrid” methods. Furthermore, structural matching is an extension of feature-based matching, so that in some matching classifications structural matching methods are considered as a subtype of feature-based matching.

#### 3.3.1 Area-based matching

The approach that is recommended for operational use with our ground-based imager system includes two area-based matching methods, as well as an appropriate matching strategy. The two area-based matching methods are explained in detail, followed by a discussion of the cloud-adapted matching strategy, which includes an appropriate point distribution (Section 3.3.1.2), approximate values and image pyramids (Section 3.3.1.3). In Chapters 4 and 5, we consider which cloud-adapted matching strategy works best for ground- and satellite-based images.

#### 3.3.1.1 Methods

In area-based matching each point to be matched is at the center of a small window of pixels in a reference image (template) and this window is compared with equally sized windows of pixels
in other images (patch). The two area-based methods tested in Cloudmap are cross-correlation matching and an adapted version of least-squares matching.

In order to compute the cross-correlation function of two windows, a template window is shifted pixel by pixel across a larger search window and in each position the cross-correlation coefficient $\sigma$ between the template window and the corresponding part of the search window is computed. The maximum of the resulting cross-correlation function defines the position of the best match between the template and the search window. Cross-correlation works fast and well if patches to be matched contain sufficient signal without too much noise and if geometrical and radiometric distortions are kept to a minimum. Another advantage of cross-correlation matching, next to processing speed, is that it is not so dependent on good approximate values in the patch image(s) as least-squares matching. So, in our case cross-correlation is a good method for obtaining some approximate matches which can then be refined with the more accurate least-squares method described below.

The Multi-Photo Geometrically Constrained Matching Software (MPGC) package developed at our Institute by Baltsavias (1991) is based on adaptive Least-Squares-Matching (LSM), first described in Gruen (1985b). With the geometric constraints, the search space is restricted along epipolar lines (Figures 3.10 and 3.11), increasing the success rate of the matching and reducing matching problems. The so-called epipolar plane, shown in Figure 3.10, is defined as the plane passing through the photogrammetric baseline and an arbitrary point P. The line of intersection between this epipolar plane and the photo plane of each image is called the epipolar line of that image ($k'$, $k''$). With known exterior and interior orientation of both images, the epipolar line in image 2 can be calculated for each point $P'$ in image 1 and vice-versa. For the calculation of the epipolar line $k''$ in image 2, points P and Q, which are identical in image space 1 ($P' = Q'$), are back-projected to image 2 to define the epipolar line as $\ell_{P'Q'}$. From $P''$, the epipolar line $k'$ through $P'$ in image 1 is calculated in the same way with an auxiliary point R. To avoid the use of slightly curved epipolar lines due to the large distortion of our wide-angle lenses, the radial and decentering lens distortion is removed from the images in the preprocessing and all subsequent steps are applied.

![Figure 3.10: Illustration of epipolar geometry (adapted from Luhmann, 2000).](image)
on the resampled images.

The geometric constraints are implemented in the matching as weighted observations, allowing them to be relaxed if the image orientation is not known with sufficient accuracy. Any number of images can be simultaneously matched and pixel and object coordinates are estimated in one common equation system. Match points are selected in one reference image, called the template, and are found in other overlapping images, called the patches. Similarity between the template and the patches is achieved by using affine geometric and two-parameter radiometric transformations. Nondeterminable affine parameters can be excluded from the estimation process and/or simpler determinable transformations can be employed (e.g. conformal, two shifts and one rotation, only two shifts). Both grey values and any functions of them (e.g. grey level gradients) can be used in matching. The MPGC LSM algorithm has sub-pixel accuracy, but the convergence radius of generally only up to 3-4 pixels is much smaller than for cross-correlation. So, MPGC matching is used in the lower pyramid levels to refine the coarse matching results from higher pyramid levels. To make optimal use of the geometrical constraints within MPGC, the points to be matched are generally selected along edges that have a sufficiently large intersection angle with the epipolar lines (e.g. at least 10°). Such points guarantee both high matching accuracy and avoidance of multiple solutions that can occur when edges are parallel to epipolar lines.

The MPGC LSM matcher can also be used for multi-view matching without geometric constraints (Figure 3.12). For all satellite-based cases, we started the data processing on the already georectified images (i.e. ATSR2-GBT, MISR L1B2 and ASTER L1B product) and, consequently, applied the unconstrained version of the matching algorithm. We plan to include geometric constraints in the MISR matching as soon as the necessary orientation parameters are available from the processing of the MISR L1B1 images with a new general sensor model for linear array sensors (Poli, 2002). However, the geometric constraints will have to be significantly relaxed due to cloud
motion.

An extension of the geometric constraints can be achieved by acquiring three simultaneous images, as described in Maas (1991). The triplet method of Maas can be shortly summarized as follows (Figure 3.13). For a point P in the first image the epipolar line in the second image is computed. Then, for all candidates on this epipolar line, the assumption of a correct match is checked in the third image by intersecting the epipolar line of P and the epipolar lines of these candidates in the third image. Because of remaining inaccuracies in the orientation of the cameras, the search space is not exactly the epipolar line but an epipolar band, implying that even trinocular matching is not always unambiguous. The success rate of correct correspondence is, however, largely increased. Maas (1996) estimated an increase of the success rate by about a factor of 5 to 100, depending on course on object geometry, data quality and number of points. Compared to particle tracking where the Maas method was primarily applied, cloud images offer additional image properties for checking point correspondences between potential triplets. Similarity measures, e.g. the cross-correlation coefficient, are thus used to further reduce unresolved ambiguities. The trinocular method can be extended to n images, if available, which will further resolve any residual ambiguities.

3.3.1.2 Distribution of matching points

Before starting an area-based matcher, the matching points have to be defined. To increase matching efficiency, only those points that are sufficient to describe the surface should be used. There are several point distribution categories (Baltavias, 1991). In the grid sampling method, a regular grid is defined in object or image space and the center point of each grid cell is matched. The extreme member of this category is to use a grid with a grid width of one pixel in image space, which means that every pixel is used for matching. In a second approach, arbitrarily distributed points are chosen. The points do not lie on a grid but are selected by an interest operator, like Förstner or Harris, so that they are more or less equally distributed over the image and have a
high probability for successful matching. Finally, in progressive sampling, which can be combined with grid sampling or arbitrarily distributed points, the point distribution is continuously densified while descending towards lower pyramid levels and higher image content. If one has already extracted some information about surface discontinuities in higher pyramid levels, one can then use this information to densify the point distribution in these regions.

With both ground- and satellite-based images, we mainly worked with arbitrarily distributed points from the Förstner or Harris operator, sometimes using progressive sampling in lower pyramid levels when too many points were rejected in higher levels during the blunder detection step. For tracking of cloud points in Meteosat images, a dense grid sampling (i.e. each pixel) was used, due to the low spatial resolution of the images compared with the coincident ATSR2 and MISR images, which allowed a precise extraction of the cloud motion field.

3.3.1.3 Approximations and image pyramids

One problematic step for most matching algorithms is determination of the first approximations for corresponding features in the other images. A detailed overview of algorithms for derivation of approximate values is given in Baltsavias (1991). Currently, most methods, including commercial matching algorithms, use multiple pyramid levels for derivation of approximate positions. In our case, pyramids are applied to reduce the maximum parallax to within 3-4 pixels, which corresponds to the usual convergence radius of the least-square matching (LSM) algorithm, as described above.

Image pyramids are a set of images derived from the original image and reduced in size down the pyramid (Jolion and Rosenfeld, 1994). In the creation of an image pyramid three parameters are used: number of pyramid levels, decimation step and generating convolution mask (“kernel”).
In our application the decimation step was set to two and a 3 x 3 Burt kernel (Burt, 1980) was applied, while the number of pyramid levels was chosen according to the estimated maximum parallax. Examples of ground- and satellite-based image pyramids are given in Figures 3.14 and 3.15. With a decimation step of two, the Burt mask M is applied at every second pixel horizontally and vertically, so the resulting higher level image \( g' \) is given as

\[
g'(i, j) = \sum_{k=-1}^{1} \sum_{l=-1}^{1} g(2i-k, 2j-l) \ast M(k+1, l+1),
\]

\[
M = \begin{pmatrix}
0.0625 & 0.125 & 0.0625 \\
0.125 & 0.25 & 0.125 \\
0.0625 & 0.125 & 0.0625
\end{pmatrix}.
\] (3.10)

Parallax between two images increases with increasing camera base and decreasing camera-to-object distance. In theory, parallax can be as large as the whole sensor dimension in the base direction for close objects that are just imaged in the right border of the left camera and the left border of the right camera. In practice, the maximum parallax for the images can be estimated from height constraints. Given the large height range of clouds, this is of course less trivial than for the generation of a digital terrain model (DTM) from a rather flat region. One advantage in matching image sequences is that a first estimate of the maximum parallax in one image pair can be derived from the maximum parallax of the previous stereo pair processed, assuming that cloud heights are not changing rapidly. However, the matching has to be carefully monitored so that any large changes in height or motion can nevertheless be detected. Since least-squares matching needs quite good approximate positions of 3-4 pixels, this may lead to the necessity of using many pyramid levels, which may lead to very small images, computational expense, fusion of discontinuous surfaces and propagation of matching errors to lower pyramid levels. Therefore, a good approach is to work with a coarse matching method (e.g. cross-correlation) on the higher pyramid levels and only apply the LSM algorithm on the lowest 2 or 3 pyramid levels.

3.3.2 Feature-based and structural matching

Feature-based matching consists of two stages: detection of interesting features and their attributes in all images and determination of corresponding features across all images. Feature
extraction and computation of feature attributes must be performed in such a way that the second stage of correspondence is easy, precise and not sensitive to errors. In contrast to our cloud matching method described above, which works with extracted points from the template image only, features are now extracted in each image individually prior to matching them. Structural, or relational, matching establishes a correspondence from the primitives of one structural description to the primitives of a second structural description (Wang, 1998), where a structural description is defined by a set of primitives (features) and their relationships. So, structural matching techniques utilize not only image features but also topological and geometrical relations among the features to determine the correspondence.

Results from feature-based and structural matching can give more information about the structure of the image content, which can be useful for subsequent segmentation. As an example for feature-based matching, we applied the edge matching algorithm developed at our Institute by Zhang and Baltsavias (2000) to the cloud stereo pair in Figure 3.7. The method first extracts edges from both the template and patch images with the Canny operator (see 3.2.2); the results are then converted into straight lines using least-square fitting. Matching is performed using geometric constraints and rich edge attributes, including radiometric and color information in the flanking regions of each edge, to construct an initial pool of match candidates. The final result is found using probabilistic relaxation and checks of the consistency of each candidate with other candidates within a local neighborhood. If the extracted lines in two cloud images are quite similar, it means that matching has a high probability of success. A sample output of the edge matching algorithm is shown in Figure 3.16. The fact that cloud boundaries are often defined by such edges can be used after matching for an easier segmentation of clouds from surrounding sky or of overlapping clouds at different heights.

Figure 3.15: Image pyramid for a satellite-based image (ATSR2). Number of levels: 4; decimation step: 2.
The MPGC matching algorithm provides several statistical measures for each matched point that can be used to detect and exclude gross errors, including the cross-correlation coefficient, a-posteriori variance of unit weight from the least-squares adjustment, size of scale, shear and shifts, number of iterations, etc. None of these measures can safely detect all blunders without excluding good points and a combination of these quality measures can provide better diagnostics. More details about these measures and their use are given in Baltsavias (1991) and Baltsavias and Stallmann (1993).

In this work both absolute and relative tests have been used. In the absolute tests, if one of the quality criteria had a poor value for a point, the point was excluded. The thresholds for these poor values were chosen carefully, as the aim was to exclude only large blunders which may distort the statistics mentioned below. Then, a relative test was performed. For the relative tests, the thresholds were derived from the statistics of all match points and were expressed as functions of the mean value and the standard deviation of each criterion, e.g. the threshold for cross-correlation was defined as the mean value minus \( n \) times the standard deviation with \( n \) usually set equal to 3. Instead of the mean and standard deviation, robust statistics like the median and median absolute deviation (MAD) can be used. In all cases, such blunder detection tests improve significantly the results, although some blunders always remain undetected and some correct...
match points are falsely rejected. The tests lead to a rejection of a certain percentage of the match points, usually about 5% in the absolute tests and 10-15% in the relative tests, depending on the matching problems and the selection of the thresholds. The blunder detection tests are applied after matching in each pyramid level to avoid propagation of incorrect results to the next lower level. After blunder detection, corresponding points can be visualized as colored points in multiple images, with color-coding according to their blunder detection results, as shown in Figure 5.15. This step allows to identify cloud areas where the matching was successful and where it was more problematic.

3.5 Segmentation and visualization

A final processing step, which will be implemented during Cloudmap2 but is not part of this work, deals with segmentation of the extracted three-dimensional cloud points into cloud objects or layers, depending on the cloud situation, and their visualization with appropriate visualization methods. Two possible visualization methods for a ground-based cloud data set are illustrated in Figure 3.17.

3.6 Software implementation

New application software (“xcv”) was implemented that combines all methods developed for the automatic derivation of cloud-base height and cloud-base motion. It includes functions for preprocessing, feature extraction, fast point approximation in patch images (e.g. cross-correlation), the core matching process and a quality control scheme, which consists of various tests on the matching statistics, as described in the previous subsections. The Graphical User Interface (GUI) has a grid structure that allows one to load stereo pairs or triplets, time sequences or both on the
screen (Figure 3.18). Normally, stereo pairs and result images are shown next to each other in the horizontal direction, while time sequences are displayed vertically. The software is based on the open source VXL libraries (VXL, 2002).
Chapter 4

Ground-based analysis

With our new stereo camera system a number of image sequences of clouds have been taken in coincidence with other ground- and satellite-based sensors. In this chapter the ground-based analysis of seven selected cases is described. First, an overview of the case studies is given, including the number of cameras, the cloud type, the time interval and the available comparison measurements. Then, the results from matching are presented, with comparisons between different matching strategies (Section 4.1). Before comparing the matching results with radiosonde, ceilometer, lidar and thermal infrared (IR) camera data (Section 4.3), these instruments are described in detail (Section 4.2). In Chapter 6 the ground-based measurements are compared and combined with satellite-based results.

Clouds are classified according to their visual appearance from the ground in a system proposed by Luke Howard in 1803 (Howard, 1803) and now adopted internationally (Rogers and Yau, 1989). The system distinguishes four major cloud types: cumulus (clouds with vertical development), stratus (clouds in flat-appearing layers), cirrus (fibrous or hair-like) and nimbus (rain clouds). The complete international classification includes dozens of subtypes that may be some combination of the four major divisions (e.g. nimbostratus), types distinguished by their altitude (e.g. altostratus), or others notable for their development (e.g. cumulus congestus). The selected ground-based cases were chosen according to cloud type and available comparison measurements (Table 4.1). Cases 1 to 3 were acquired during the MAP Campaign, while cases 4 to 7 were obtained at the airport of Zürich-Kloten.

The seven cases were analyzed in detail with our cloud-adapted matching algorithm, described in Chapter 3. Different matching strategies were tested, including use of original images versus preprocessed images, various weights of the geometric constraints, different patch sizes, use of more than two cameras and several quality control options (Section 4.1). The general processing scheme is illustrated in Figure 4.1. As mentioned in the introduction, three methods of validation can be used to obtain accuracy estimates for the stereo cloud-base height results: visual analysis at a photogrammetric workstation, comparison with semi-automatic measured points and
comparison with other instrument data.

For the first method the right and left image of the stereo pair are superimposed at a photogrammetric workstation in such a way that the overlap region can be seen in stereo. An overview of available stereo-vision formats for video and computer graphics can be found in Petrie (2001) or at StereoGraphics (2002). A simple traditional method is to display the left and right images side-by-side on a single display monitor and to view them through a lens or mirror stereoscope. Another widespread method (due to its low-cost) is the anaglyph technique where one image is shown in red and the other image in green (or blue) with red-green anaglyph “glasses”. Because anaglyph images not only work well for single display monitors but also for printouts, we use this technique for the presentation of stereo images throughout this thesis. At digital photogrammetric workstations polarizing screens and viewing with polarized glasses are usually applied. With the polarization method the two images are switched at an appropriate frequency by the computer screen, in synchronization with the emitter frequency of the glasses. Moreover, matched points can be drawn in each of the images. If the points were matched correctly, they will lie on the stereo observed “surface”. Outliers will appear as “floating” points either far above the surface or as “holes” within the surface. Other quality control visualization methods are the overlay of height contours on the original image or hill-shading of the triangulated surface model.

In contrast to digital surface model (DSM) generation of solid objects (e.g. houses), one can easily understand that the detection of blunders with this visual method is much more difficult for “fuzzy” structured objects like clouds. Of course, larger outliers can still be found, but small deviations from the correct height are impossible to detect. As the largest outliers are, in general, thrown out during the quality control step, this visual validation method does not have the same importance for cloud measurements as for other applications. Measurement of 3D validation points at the digital photogrammetric workstation is not recommended for the same reason; instead, we recommend matching pairs (or triplets) of points semi-automatically (i.e. manual location of approximate values in patch images) between the images. Validation of the matching results with

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>#cams</th>
<th>Cloud type</th>
<th>Δt [s]</th>
<th>Radiosonde</th>
<th>Ceilometer</th>
<th>Lidar</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>08-10-1999</td>
<td>2</td>
<td>Ac</td>
<td>30</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>13-10-1999</td>
<td>2</td>
<td>Ci+Cs</td>
<td>120</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>20-10-1999</td>
<td>2</td>
<td>Cs</td>
<td>120</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>27-09-2001</td>
<td>3</td>
<td>Contrails</td>
<td>60</td>
<td></td>
<td>x</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>29-09-2001</td>
<td>3</td>
<td>St</td>
<td>60</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>12-04-2002</td>
<td>2</td>
<td>Ac+Cs</td>
<td>60</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>19-04-2002</td>
<td>2</td>
<td>Sc+Ci</td>
<td>60</td>
<td></td>
<td>x</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Overview of ground-based comparison cases. Cloud types: Ci=Cirrus, Cs=Cirrostratus, Ac=Altostratus, St=Stratus, Sc=Stratocumulus, Contrails=persistent cirrus clouds caused by air traffic. Δt: time difference between subsequent stereo pairs.
these semi-automatically measured points is described in the next section for various matching strategies. As the same orientation parameters are used for the forward intersection of the automatically matched points and the semi-automatically matched validation points, the validation results only describe the accuracy of the matching. Any errors in the cloud-base heights due to inaccuracies in the orientation data can only be detected with independent validation data. Therefore, the cloud-base height results are compared with other meteorological data in Section 4.3. Unfortunately, none of the available comparison instruments has a much higher height accuracy than the stereo method (see Table 4.4) which would be needed for a true validation. Nevertheless, the comparison cases illustrate the potential accuracy of the stereo camera system.

### 4.1 Accuracy analysis of matching results

#### 4.1.1 Accuracy depending on cloud type

Comparisons of DSM and semi-automatically measured points within the overlapping area of three of the case study stereo pairs are illustrated in Table 4.2. For the 08/10/1999 images with a mean cloud height of 4000 m ASL the expected height accuracy according to Equation 2.2 is about 7.2 m, while for the 13/10/1999 case with a mean cloud height of 10500 m ASL the expected height accuracy is about 58 m. For the 19/04/2002 case the expected height accuracy, assuming one pixel measurement accuracy for the semi-automatically measured points, is 4.7 m.

From the results we can see that the theoretical accuracy is reached in the first and second case, while the deviations are slightly larger in the third case. The first case, with broken mid-level altocumulus clouds, is obviously the most accurate. Some larger deviations are observed with high, semi-transparent, hardly visible Cs clouds (13/10/1999) and with textureless areas in Sc or St clouds (19/04/2002). While high, thin cirrostratus are difficult to measure by most instruments,
except lidar if there are no underlying clouds and the signal-to-noise ratio is sufficiently high, the height of Sc and St can be reliably determined from ceilometer data. Another point to consider is that the accuracy of this comparison of the interpolated DSM with specific manually measured locations is dependent on the density of points which were matched within the field of view (FOV) of the cameras. Often, the number of extracted points is lower for poorly defined cloud structures, so that some deviations in the comparison can be caused by the interpolation, especially near DSM discontinuities (e.g. two cloud layers as in the 13/10/1999 case).

### 4.1.2 Accuracy enhanced vs. non-enhanced

The effect of preprocessing the images with the Wallis filter was tested on two distinct cloud cases: a well-structured Ac scene and a scene with a lower Ci layer and a higher, nearly textureless Cs layer. Two sets of results were calculated for each case, one with the original images and a second version with Wallis filtered images. For the first case we find that the enhanced version performs slightly better on average, but with maximum errors that are clearly reduced. For the second case preprocessing significantly improved the cloud-base height retrieval (Table 4.3).

<table>
<thead>
<tr>
<th>Images</th>
<th>Preprocessing</th>
<th>Number of points</th>
<th>Average [m]</th>
<th>RMS [m]</th>
<th>Max [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/10/1999</td>
<td>original images</td>
<td>62</td>
<td>-1.77</td>
<td>9.5</td>
<td>-47.9</td>
</tr>
<tr>
<td>08/10/1999</td>
<td>preprocessed</td>
<td>62</td>
<td>-1.31</td>
<td>8.7</td>
<td>-32.6</td>
</tr>
<tr>
<td>13/10/1999</td>
<td>original images</td>
<td>47</td>
<td>17.0</td>
<td>98.9</td>
<td>563.8</td>
</tr>
<tr>
<td>13/10/1999</td>
<td>preprocessed</td>
<td>47</td>
<td>15.6</td>
<td>60.1</td>
<td>413.6</td>
</tr>
</tbody>
</table>

Table 4.3: Statistical measures of the differences between the DSM results from the cloud-adapted MPG C LSM algorithm and the manual measurements for non-preprocessed and preprocessed images. Positive values indicate CBH results from automatic measurements that are greater than their corresponding manually derived values.
differences between multiple cameras are present at lower sun elevation angles and with base lengths greater than 1 km. As our image sequences were mainly recorded during satellite over-flight times around 10:00 - 11:00 UTC with base lengths of 80 - 850 m, radiometric influences in our images are not as significant.

4.1.3 Use of 3 cameras vs. 2 cameras

In September 2001 we tested the usefulness of an additional third camera. As shown in Figure 2.7, the third camera was installed slightly northwards of camera 1 with a base length of 80 m. A comparison of different three-camera geometries is given in Maas (1991). With a triangular arrangement of the three cameras, the epipolar line intersection method, illustrated in Figure 3.13, can be applied. With a collinear arrangement (i.e. all three cameras in one line) the search space is reduced along the common epipolar line. In the results of particle detection Maas (1991) showed that the triangular arrangement is only slightly superior to the collinear arrangement. The optimal collinear configuration is with the third camera situated at the center of the long base line while an equally-sided triangle is optimal for a triangular arrangement. For applications like cloud matching, the triangular arrangement is better suited than the collinear arrangement as it increases the constraints for linear features. The triangular arrangement with the associated epipolar line intersection method has the further advantage in our application that the epipolar lines have two different directions (or three different directions by considering switching of the template image). Therefore, point selection with the Förstner operator can be extended to the various intersection possibilities between epipolar lines and cloud features. In Figures 4.2 and 4.3 three image matching is illustrated for a contrail with two different template-patch configurations.

In the first example image 2 is the template so the resulting epipolar lines in images 1 and 3 are rotated by about -5° and +15° with respect to the x-direction, therefore favouring matching of near-
vertical cloud structures. In the second example, with image 1 as the template image, the epipolar line angles in images 2 and 3 are rotated by -5° and +75°, respectively, thereby allowing matching of horizontal cloud features. Of course, the directions of the epipolar lines could be optimized with a three-camera arrangement in an equally-sided triangle or with a four-camera arrangement if permitted by the available field logistics.

Another advantage, which is obtained with the chosen three-camera setup, is the three different base lengths. While the minimal detectable cloud height according to the overlap area (Equation 2.1) is 430 m for cameras 1 and 2, the minimal height is only 63 m for cameras 1 and 3. In contrast, the height accuracy (Equation 2.2) is reduced from 12.1 m to 83.3 m for an average cloud height of 4 km and a parallax accuracy of 1 pixel. So, lower cloud heights can be retrieved with the smaller base length alone, while for higher clouds the preliminary results from the small base length camera combination are taken as approximations for subsequent matching between the cameras with larger horizontal separation.

One can also make use of the three-camera setup in quality control. Two independent matching processes are run with the same point set extracted from image 1: one with cameras 1 and 2 and the second one with cameras 1 and 3. All points that were matched in both camera combinations are then compared with each other in the postprocessing. If the error ellipses of the two retrieved heights do not overlap, the point is rejected in the quality control. The size of each error ellipse should be a function of the retrieved cloud height to take into account the dependence of the height accuracy $\sigma_z$ on cloud height, so for example 1.5-2.0 times the corresponding height accuracy.
The same algorithms can be used for deriving three-dimensional cloud motion by matching corresponding features in stereo image sequences. Various time intervals ranging from 30 s to 120 s were tested (Table 4.1) to evaluate the limits of cloud tracking with this specific matching algorithm. The tests showed that 120 s is too long in many cases. Not only are there large displacements for fast moving clouds, but more problematic are significant changes in cloud structure on this time scale (Figure 4.4). For larger time differences the use of our matching algorithm is therefore no longer appropriate for tracking. Other specific tracking methods have to be applied to the image sequences, e.g. deformable models such as active contours (Blake and Isard, 1998). Another approach that worked well for tracking convective clouds in satellite-based images is based on level set methods, as described in Papin (1999). A similar approach that takes into account the different spatial resolution of ground systems could probably allow tracking of specific features in ground-based images with longer time intervals.

An additional time constraint is the amount of cloud displacement, especially for lower clouds, so that the overlapping area between subsequent images gets too small. The amount of displacement (in pixels) can be calculated as

\[(dx, dy) = \Delta t \cdot (u, v) \cdot \frac{c}{h} \cdot \frac{\text{width}}{x},\]

where \((u, v)\) are the components of cloud motion speed in the x- and y-direction [m/s], \(x\) is the

Figure 4.4: Problems that arise in image tracking if the time difference between two consecutive stereo pairs is too large. Top: stereo pair at time \(t_0\); bottom: stereo pair at time \(t_1\). There is a 2-minute time difference for these images obtained on 13/10/1999.

4.1.4 Sequence-based analysis

The same algorithms can be used for deriving three-dimensional cloud motion by matching corresponding features in stereo image sequences. Various time intervals ranging from 30 s to 120 s were tested (Table 4.1) to evaluate the limits of cloud tracking with this specific matching algorithm. The tests showed that 120 s is too long in many cases. Not only are there large displacements for fast moving clouds, but more problematic are significant changes in cloud structure on this time scale (Figure 4.4). For larger time differences the use of our matching algorithm is therefore no longer appropriate for tracking. Other specific tracking methods have to be applied to the image sequences, e.g. deformable models such as active contours (Blake and Isard, 1998). Another approach that worked well for tracking convective clouds in satellite-based images is based on level set methods, as described in Papin (1999). A similar approach that takes into account the different spatial resolution of ground systems could probably allow tracking of specific features in ground-based images with longer time intervals.

An additional time constraint is the amount of cloud displacement, especially for lower clouds, so that the overlapping area between subsequent images gets too small. The amount of displacement (in pixels) can be calculated as

\[(dx, dy) = \Delta t \cdot (u, v) \cdot \frac{c}{h} \cdot \frac{\text{width}}{x},\]

where \((u, v)\) are the components of cloud motion speed in the x- and y-direction [m/s], \(x\) is the
larger dimension of the sensor [mm], width is the larger sensor dimension [pixels], c is the focal length [mm] and h is the cloud height [m above ground]. In reality, cloud speeds are generally larger at higher altitudes so that for usual cloud velocities of 10-20 m/s the cloud displacement for a 30 s interval is still small enough to ensure a large overlapping area for a three-dimensional cloud-base motion retrieval.

An advantage of a sequence-based analysis against analysis of a single time step is the additional height and motion constraints which are introduced with multiple time steps, as illustrated in Figure 4.5. The search space of the cross-correlation matcher for the derivation of the approximate values in the highest pyramid level of the second and subsequent time steps is significantly reduced, which results in higher search speed and higher reliability. For quality control some points can also be matched to other images. For example, matching of point P' in image 1_time0 to point Q' in image 2_time0, then tracking of point Q' to point Q'' in image 2_time1; finally, matching of Q'' to image 1_time1 and comparison of the location of this point P'' with the tracked point P'' (Figure 4.5).

Note that there are obvious differences between air motion (i.e. wind), the motion of individual cloud particles and the observed “cloud object” as a whole. As described in Rogers and Yau (1989), individual water droplets and ice crystals that constitute a cloud are transitory, created by condensation and lost by evaporation or precipitation. The cloud, or cloud system, continues to live by the steady creation of new droplets as other ones cease to exist. A cloud may be thought of as a kind of wave or disturbance through which the droplets move. It propagates in the direction of new drop formation and does not necessarily move as an entity with the wind at cloud level. Individual droplets, crystals and precipitation particles, however, move with the velocity of the air surrounding them plus their fall velocity relative to the air. As a cloud is an assembly of tiny droplets or crystals and densities of several hundred particles per cm³, we will never observe single particles within our images that have a resolution of 0.06 % of the CBH, corresponding to...
a resolution of 0.6 m for a CBH of 1 km AGL to 7.2 m for a CBH of 12 km AGL. In contrast to the lower resolution satellite images, which will be discussed in Chapter 5 and where the extracted cloud motion clearly describes the movement of the cloud patterns as a whole, we can observe regions within the ground-based images where the extracted cloud motion describes smaller scale turbulence.

### 4.2 Alternative data for CBH and CBW comparisons

Due to the spatially variable, rapidly changing and complex characteristics of clouds, their observation or measurement is still a demanding task in meteorology, especially in aviation weather nowcasting and forecasting. Besides traditional visual observations of the cloud situation and present weather, which are still maintained at most airports and many climatological stations around the world with a frequency of 30 min to 6 h, many sites have recently added present weather sensors and sophisticated cloud measurement instruments for additional reliability and security. Going from visual observations to lidar and radar measurements, the question of definition of a cloud and of the cloud boundaries becomes important.

A cloud can be simply defined as a collection of particles in the sky; these particles are water droplets or ice crystals (Venema, 2000). Cloud boundaries are then seen by a visual observer where the number concentration of particles is sufficient to scatter or absorb light waves effectively enough for the human eye to detect. However, with other instruments the cloud boundaries may be seen at other positions, because of the different wavelength and the different scattering sensitivity to cloud particles. One extreme example is subvisible cirrus clouds which have such low ice crystal densities that they are completely transparent in the visible, yet nearly opaque in the infrared (Kaercher, 2002). Currently, there is still the attempt to turn ceilometer, lidar and radar measurements into binary cloud base/top height quantities. The WMO has recently published recommendations on how to refine the practices for reporting total cloud amount and cloud height (?). For cloud height reporting, they recommend replacing the typical reports on cloud-base height with a report containing a profile of the optical extinction coefficient.

The main features of the various measurement techniques for cloud-base and cloud-top height retrieval are summarized in Table 4.4. As shown in Table 4.1, the CBH results from our ground-based measurements at Mels (MAP) and Zürich-Kloten airport can be compared with four instruments: radiosonde, ceilometer, Doppler lidar and IR camera images. These instruments and their data are described in the coming subsections. Unfortunately, there are no cloud radars installed in Switzerland, so that no radar data with a suitable wavelength are available for CBH validation. For CTH comparison and validation two selected cases at Chilbolton (UK) include coincident ground-based cloud radar measurements (Table 5.7). Next to cloud radars, radiosonde data offer CTH comparisons with reasonable accuracy, at least for low and middle clouds up to about 8 km. Of course, many other satellite-based cloud-top height/pressure (CTP) retrieval methods exist be-
sides the stereo technique, which allows for interesting comparisons between products derived with the different techniques (Section 5.3). As shown in Chapter 6, validation of satellite-based CTH and CTW of vertically thin clouds is possible with our new ground-based imager system, while for clouds with larger vertical extent, or for non-broken multilayer cloud systems, the ground- and satellite-based measurements can be combined for a better understanding of the cloud situation.

The values shown in Table 4.4 are based on the data of the operational Payerne radiosondes (Pierre Jeannet, personal communication), the Vaisala 25K ceilometer (Vaisala, 2002), the transportable wind lidar (TWL) installed during MAP (Philippe Drobinsky, personal communication) and the Chilbolton radar (Robin Hogan, personal communication). We emphasize that a quantitative estimate of cloud base/top height assignment accuracy is not possible for any of the instruments, based on the complexities of cloud boundary definition described above. For the stereo camera system, CBH accuracy is a measure of how accurate the heights of the matched cloud features can be retrieved. These retrieved cloud features do not necessarily correspond with the actual cloud boundaries (i.e. first occurrence of cloud particles). For most clouds, however, stereo- scopically matched features are a good proxy for the bottom boundaries of clouds because most clouds become optically thick within a few hundred meters from their boundaries. For lidar and radar CBH/CTH accuracy, the maximum achievable accuracy is given by their vertical spatial resolution, which are reported as CBH/CTH accuracy in Table 4.4. The actual cloud boundary retrieval accuracy is dependent on the distribution of the droplets/crystals within the cloud. Multiple cloud layers and clouds with specular reflections (i.e. strong reflection of light from horizontally aligned ice crystals) can pose problems for lidar, while radar has problems at the base of water clouds or in large regions of small particle ice clouds that have low radar reflectivities. Therefore, a combined lidar/radar observation of clouds is highly recommended as reported in, for example, Clothiaux et al. (2000), Donovan et al. (2001) and Venema (2000).

Several instruments outside Switzerland provide higher accuracy cloud height data. The newest ceilometer models (e.g. Vaisala LD-40) and cloud-optimized lidars (e.g. lidar of “Site Instrumental de Recherche par Télédétection Atmosphérique” SIRTA near Paris) provide a larger height range

<table>
<thead>
<tr>
<th>Area</th>
<th>Visual observation</th>
<th>Radiosonde SRS-400</th>
<th>Ceilometer Vaisala 25K</th>
<th>Scanning lidar LMD-TWL</th>
<th>Radar 94GHz Chilbolton</th>
<th>Stereo camera “Skycam”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Every 0.5 - 6 h</td>
<td>Every 6 - 12 h</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>Range</td>
<td>&lt; max. visible mountain height</td>
<td>&lt; 8-10 km</td>
<td>&lt; 8.9 km</td>
<td>&lt; 15 km</td>
<td>&lt; 15 km</td>
<td>no limit</td>
</tr>
<tr>
<td>CBH accuracy</td>
<td>20-30% of CBH</td>
<td>100-200 m</td>
<td>2% of CBH</td>
<td>&gt; 200 m</td>
<td>&gt; 60 m</td>
<td>see Equ. 2.2</td>
</tr>
<tr>
<td>CTH accuracy</td>
<td>-</td>
<td>200-300 m</td>
<td>-</td>
<td>-</td>
<td>&gt; 60 m</td>
<td>-</td>
</tr>
<tr>
<td>Material costs</td>
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<td>$800 000</td>
<td>$1 000 000</td>
<td>$20 000</td>
<td></td>
</tr>
<tr>
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<td>acquisition</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 4.4: Comparison of different instruments for measuring CBH and CTH.
and CBH accuracy. The Doppler lidars installed at SIRTA can also penetrate optically thinner clouds and thereby provide estimates of cloud-top height. Another measurement technique with a high accuracy potential for cloud-base height retrieval are Raman lidars (Goldsmith et al., 1998). Their retrieval accuracy depends strongly on the signal-to-noise ratio, which is more favorable during nighttime. Daytime operation is more difficult because of the need to detect the relatively weak Raman signal in the presence of strong scattered solar radiation. At the ARM Southern Great Plains site a Raman lidar has been operationally installed since April 1998 (Ackerman et al., 2003).

Before providing detailed descriptions of each measurement method shown in Table 4.4, a few words regarding the validation of cloud-base motion are in order. In particular, validation of cloud-base motion is even more difficult than validation of cloud-base height, as most of the conventional instruments measure the wind speed/direction of the air and not of the clouds. In some cases cloud motion can correspond to the wind at cloud base, but in most cases the comparison can be misleading (e.g. orographic foehn clouds). Currently, there is no operational instrument in Switzerland that can measure cloud-base motion. Estimation of cloud motion through visual observations is possible in some cloud situations for the motion direction, but much less so for the actual cloud speed. However, none of the operational visual observations currently include an estimation of cloud motion. Therefore, the only validation of ground-based cloud-base motion retrievals is through comparisons with satellite-based cloud motion data for vertically thin clouds (e.g. 13/10/1999 cirrus case). For these comparisons we use data from MAP Meteosat-6 5-minute Rapid Scans and operational Meteosat-6 10-minute Rapid Scans since 2001 (Chapter 6).

4.2.1 Visual observations

Visual observations of current weather, including estimation of cloud amount, cloud depth, cloud type and cloud-base height, are performed half-hourly at the airport stations, 3-hourly at the main automatic climate stations, 4-hourly at the aero stations and 6-hourly at all other climate stations of MeteoSwiss. These observations are sometimes performed by different persons at the same station so that there is subjectivity in the estimated values not only between stations but also within the time series of one station. As described in Table 4.4, the height of cloud base can be estimated with an accuracy of about 20-30% of the height. Height estimation is done according to cloud type and with the help of surrounding known mountain heights. Above the highest visible mountain top, accuracy rapidly drops to a few kilometers. Estimation of cirrus cloud-base heights from ground-based visual observations is nearly impossible with heights being underestimated in most cases. Due to low accuracy and data problems, visual observations from the MeteoSwiss stations within the MAP Rhine Valley area (i.e. Weesen and Vaduz) were not useful for comparison with our imager results. While the quality of visual observations at the airports was better and more consistent between observers, the accuracy of these estimates was also too low for any quantitative comparison with the stereo imager results.
4.2.2 Radiosondes

Current observing systems that provide information about the horizontal and vertical distribution of clouds are often limited by “obscuration effects”. Surface observers and optical instruments sense only the lowermost cloud layer, while present day satellites sense only the uppermost cloud layer, requiring some assumptions to characterize the full vertical cloud structure. Active sensors with appropriate wavelengths, such as cloud radars (Section 5.3.2) and lidars (Sections 4.2.4 and 4.2.3), can profile the whole vertical cloud distribution. However, their high price hinders their operational deployment in large numbers, so that global coverage is not attainable. In contrast, radiosonde data have the advantage of long records (about 40-50 years), extensive coverage, especially in the Northern Hemisphere, and rather low cost. Despite various research efforts to increase the use of satellite data in NWP model assimilation, most operational numerical models still heavily rely on vertical profiles obtained from operational radiosonde ascents.

In Europe, the operational radiosoundings by each National Weather Service are coordinated within EUMETNET (EUMETNET Radiosonde, 2002). In Switzerland, there is one permanent sounding station at Payerne (46.82 N, 6.95 E) operated by MeteoSwiss. The 00:00 UTC and 12:00 UTC soundings are from fully equipped sondes that measure pressure, temperature, dew point and wind, while the 06:00 UTC and 18:00 UTC soundings provide only wind measurements. For the Payerne sounding, the Swiss sonde SRS-400 from Meteolabor is used (Richner, 1999).

During the MAP SOP in autumn 1999, several temporary radiosonde stations were set up in the three target areas. By far the largest sounding density was achieved in the target area “Rhine Valley” as seven temporary radiosonde stations were operated by the Swiss Army in the greater Rhine Valley area. They consisted of two types of sondes: low-level sondes, measuring temperature and wind, and high-level sondes, measuring pressure, temperature, humidity and wind. The five MAP low-level sounding stations did not allow a reliable cloud boundary retrieval from the temperature and wind profiles, so these soundings were not considered in our comparison. The high-level sounding stations of Diepoldsau (47.37 N, 9.66 E) and Masein (46.71 N, 9.43 E) were equipped with ground station P-760 receivers and used the same SRS-400 sonde as the operational soundings from Payerne. While the operational version of the SRS-400 measures the dewpoint temperature with a dewpoint mirror for high precision humidity values, the MAP SRS-400 sondes were equipped with a carbon element for relative humidity measurement. Consequently, the accuracy of the SRS-400 sounding data was ± 2 hPa for pressure, ± 0.3 K for temperature and ± 2% for relative humidity. The following approximation is recommended by the WMO to calculate the dewpoint temperature $T_d$ from the temperature $T$ and relative humidity $RH$ (Richner, 1999):

$$T_d = \frac{b[(b + T) \ln\left(\frac{RH}{100}\right) + aT]}{ab - (b + T) \ln\left(\frac{RH}{100}\right)}$$ (4.2)

where $a=17.502$ and $b=240.97$.

At Zürich-Kloten airport, no soundings are allowed within a certain radius around the airport area. With special agreement from the airport authority, we were able to launch radiosonde balloons
from ETH-Hönggerberg with a horizontal distance of only 5 km from our camera locations (Figure 4.6 left) which is close enough for getting a realistic description of moist layers in the atmosphere over Zürich-Kloten. Our ETH soundings use the radiosonde system and Mark II microsonde from Sippican Inc. (Sippican, 2002). These sondes measure pressure, temperature and relative humidity and their light weight and low cost facilitates one-person launches and allows the use of a smaller balloon. Temperature is measured with a thin rod thermistor with an indicated accuracy of ± 0.2 K. A carbon hygristor measures relative humidity with an accuracy of ± 2%. Both parameters are sampled once per second throughout the flight. The sensor information is transmitted continuously to the ground receiving station. Given a mean duration of 30-40 minutes to reach the tropopause, the sondes were launched about 15 minutes before the estimated satellite overpass time of ERS-2 or EOS-Terra to ensure useful comparison data over the whole vertical profile. Of course, with a priori knowledge of the mean cloud height, the time span between the start time of the sounding and the overpass time could be adjusted accordingly. As soundings indicate the current cloud layers, as well as potential cloud layers within about ± 1 h (see explanation below), their timing is not so crucial.

For a cloud to form a large volume of air must be cooled below its dew point. In the atmosphere cooling is most often created by the approximately adiabatic expansion of ascending air, but it can also be caused by radiative cooling or by mixing of air masses with different temperatures and humidities. Radiosondes do not directly measure the vertical distribution of clouds, so that cloud layers have to be inferred from their temperature and humidity profiles.

A common visual method to detect cloud layers is to plot the temperature and dewpoint temperature profiles (Figure 4.7 left). At height levels where there is a small difference between the two temperatures (visible in the plots at heights where the two profiles approach each other) the atmosphere is saturated and cloud occurrence is likely. However, such saturated, or nearly saturated, layers are no guarantee for the actual presence of clouds.

Instead of inspecting the temperature differences, the relative humidity profile can be analyzed (e.g. Baum et al. 1995; Wang and Rossow 1995; Wang et al. 2000). The Wang and Rossow (WR) method works purely with thresholds on relative humidity (Figure 4.7 center). For temperatures below 0°C the relative humidity values over water are converted to the corresponding relative humidity values over ice in the WR approach.

Another method for estimating cloud-base heights from radiosonde data, the Chernykh and Eskridge (CE) method, is described in Chernykh and Eskridge (1996), Chernykh and Alduchov (2000) and Chernykh et al. (2001) (Figure 4.7 right). In Naud et al. (2003), the results of the CE and WR method are compared against ARM SGP radar, lidar and ceilometer cloud boundary data. The difficult aspects of the CE method are the choice of the height resolution for estimation of the temperature and relative humidity derivatives and the non-synchronized time lags of the temperature and humidity sensors (Seidel and Durre, 2003; Chernykh et al., 2003). The time lag of a thermistor rod is 4.5 s at 1000 hPa and 10.6 s at 100 hPa, while the SRS-400 nickel wire thermistor has a time lag of 0.02 s at 1000 hPa and 0.06 s at 100 hPa. For a typical carbon hy-
Figure 4.6: Left: launch of a radiosonde balloon from ETH-Hönggerberg; right: the Mark II microsonde that was used for the ETH soundings.

Figure 4.7: Illustration of cloud boundary retrieval methods from radiosonde profiles. Left: classical visual method with temperature (solid line) and dewpoint temperature (dashed line) profiles; center: Wang/Rossow (WR) method with relative humidity over water (solid line) and over ice (dashed line); right: Chernykh/Eskridge (CE) method (extracted potential cloud layer shown as grey-shaded bars).
The time lag varies between 0.3 s at 20°C, 1.2 s at 0°C to 15 s at -30°C (Christian Häberli, personal communication).

For a better diagnosis, the soundings and results from each method are plotted next to each other to allow the direct comparison of the individual method results. These combined plots from all soundings are presented in the Appendix as Figures A.1 to A.9.

4.2.3 LMD Transportable Wind Lidar

A comparison instrument that was available during the MAP-SOP was the Transportable Wind Lidar (TWL) from the Laboratoire de Météorologie Dynamique (LMD), France (LMD, 2002) (Figure 4.8). The lidar was located at Vilters, which was within a few kilometers distance of the camera locations (Figure 2.6). The LMD lidar operates at 10 μm, so it is less sensitive than the ceilometer to smaller particles. The lidar is able to detect the base and top of thin cirrus with an accuracy of about 200-250 m (Philippe Drobinsky, personal communication). Instead of only pointing vertically, the lidar has a scanning mode for obtaining hemispheric scans of the radial wind velocity field. During the MAP SOP, the LMD lidar was mainly operating in this second mode (“wind mode”) to study the Foehn flow splitting phenomena near Sargans (Drobinsky et al., 2001). Therefore, only one coincident cloud case between the lidar and camera system could be found (20/10/1999).

4.2.4 Ceilometers

Today, operational ceilometers are installed at most airports around the world. A ceilometer measures the height of cloud base above ground level. It transmits laser pulses vertically into the atmosphere and measures the time delay for the pulses to return to the ceilometer after reflection by small water droplets in the clouds. Up to three cloud layers can be detected. However, as ceilometer lasers have a wavelength around 900 nm, there is significant scattering and reflection by thicker clouds and rain, so that in many situations only the base of the lowest layer is detected.
The Vaisala 25K ceilometer (Vaisala, 2002) uses a pulsed diode, InGaAs MOCVD laser at a wavelength of 905 nm that transmits approximately 5’000 light pulses vertically towards the clouds each second. As the backscatter signal of a single pulse is weak, signals are summed over intervals of 15 s to 30 s to improve signal-to-noise ratios. Instrument software processes these signals into cloud-base height values by applying a threshold on the return signal to distinguish between pure noise and noise summed with a cloud signal. The resolution of the Vaisala 25K ceilometer is 50 ft (i.e. about 16 m) with an accuracy of ±2% of the cloud height. The maximum detection height of the Vaisala 25K ceilometer is around 25’000 ft or 8 km. Newer ceilometer models (e.g. Vaisala LD-40) allow cloud-base detection up to 15 km, but none of these newer instruments are yet installed in Switzerland.

Next to the three camera locations four operational Vaisala 25K ceilometers were installed by MeteoSwiss (Figure 4.8), providing point validation for the stereo-derived cloud-base heights. The ceilometer locations are shown in Figure 2.7 and the exact Swiss coordinates, altitudes, tilt and azimuth angles of the ceilometer pointing directions are given in Table 4.5. Tilting of the ceilometer beam is commonly employed to avoid specular reflection and to protect against falling rain drops or snow flakes, which can adversely affect the ceilometer CBH detection. However, recent studies do not support these theoretical advantages of tilting (Giles, 2001). The disadvantage of a rather large tilt angle is that the horizontal location of the detected cloud is dependent on the actual cloud height.

![Table 4.5: Ceilometer locations at Zürich-Kloten airport.

<table>
<thead>
<tr>
<th>Location</th>
<th>Coordinates [m]</th>
<th>Height [m ASL]</th>
<th>Tilt angle [°]</th>
<th>Azimuth [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochfelden (HF)</td>
<td>680’190</td>
<td>264’080</td>
<td>2</td>
<td>330</td>
</tr>
<tr>
<td>MiddleMarker (MM)</td>
<td>682’200</td>
<td>259’970</td>
<td>6</td>
<td>340</td>
</tr>
<tr>
<td>Runway 14/16 (RW)</td>
<td>682’710</td>
<td>259’350</td>
<td>0</td>
<td>340</td>
</tr>
<tr>
<td>Bassersdorf (BD)</td>
<td>688’350</td>
<td>255’450</td>
<td>9</td>
<td>270</td>
</tr>
</tbody>
</table>

The Vaisala 25K ceilometer uses a pulsed diode, InGaAs MOCVD laser at a wavelength of 905 nm that transmits approximately 5’000 light pulses vertically towards the clouds each second. As the backscatter signal of a single pulse is weak, signals are summed over intervals of 15 s to 30 s to improve signal-to-noise ratios. Instrument software processes these signals into cloud-base height values by applying a threshold on the return signal to distinguish between pure noise and noise summed with a cloud signal. The resolution of the Vaisala 25K ceilometer is 50 ft (i.e. about 16 m) with an accuracy of ±2% of the cloud height. The maximum detection height of the Vaisala 25K ceilometer is around 25’000 ft or 8 km. Newer ceilometer models (e.g. Vaisala LD-40) allow cloud-base detection up to 15 km, but none of these newer instruments are yet installed in Switzerland.

Next to the three camera locations four operational Vaisala 25K ceilometers were installed by MeteoSwiss (Figure 4.8), providing point validation for the stereo-derived cloud-base heights. The ceilometer locations are shown in Figure 2.7 and the exact Swiss coordinates, altitudes, tilt and azimuth angles of the ceilometer pointing directions are given in Table 4.5. Tilting of the ceilometer beam is commonly employed to avoid specular reflection and to protect against falling rain drops or snow flakes, which can adversely affect the ceilometer CBH detection. However, recent studies do not support these theoretical advantages of tilting (Giles, 2001). The disadvantage of a rather large tilt angle is that the horizontal location of the detected cloud is dependent on the actual cloud height.

### 4.2.5 Infratec IR camera

During two days in September 2001, we were able to make some measurements with a thermal infrared camera simultaneously with our three optical CCD cameras. The IR camera was installed about 1 m away from camera 1 on the roof of the MeteoSwiss Beobachterhaus Oberglatt at Zürich-Kloten airport (Figure 4.9). The IR camera lens was adjusted horizontally, as were the CCD cameras, so that near-vertical images of the sky and clouds were taken. The acquisition frequency of the camera was set to 30 s.

The IR camera was a VARIOSCAN HR Compact from InfraTec (Infratec, 2002) developed in cooperation with Jenoptik Jena LaserOptikSysteme (Jenoptik, 2002). The instrument is operated...
in the spectral range from 8 to 12 μm with a permanently cooled (stirling cooler, thermoelectric or liquid nitrogen) HgCdTe detector. With the current camera model, the temperature range was from -40°C up to around 1'000°C with a resolution of about ± 0.03 K at 30°C and an accuracy less than 2 K below 100°C. Of course, this temperature range is not yet optimized for atmospheric applications, where temperatures colder than -40°C would be of great interest and temperatures higher than +40°C are of no interest. The FOV of the lens is 30° x 20°, which is much smaller than the FOV of our cameras (Figures 4.9 and 4.15) and the spatial resolution of the sensor is 360 x 240 pixels. Unfortunately, the IR camera system was not yet weatherproofed; especially the lens had to be protected against any water drops.

Thermal infrared cameras have the ability to measure the brightness temperature of an object, which provides information about cloud-base height, as described later in Section 4.3.4. Actually, a single infrared camera can only be used for cloud height determination of either optically thick clouds with an emissivity of about 1.0 or for clouds from which the emissivity is roughly known from external data. It is therefore also not possible to report an a priori CBH retrieval accuracy. We do not recommend a single IR camera for CBH retrieval at all because of the above mentioned dependence on cloud emissivity. The advantage of IR cameras is their similar characteristics both during the day and at night. A stereo setup of at least two IR cameras would clearly be an interesting approach for night-time CBH retrievals.

4.3 Comparison results

Validation of the matching results with semi-automatically measured points was described in Section 4.1 for various matching strategies. As the same orientation parameters are used for the forward intersection of the fully automatically matched points and the semi-automatically matched
validation points, the validation results only describe the accuracy of the matching. Any errors in
the cloud-base heights due to inaccuracies in the orientation data can only be detected with inde-
pendent validation data. Therefore, the cloud-base height results are in the following compared
with other meteorological data. Unfortunately, none of the available comparison instruments has
a much higher height accuracy than the stereo method (see Table 4.4) which would be needed
for a true validation. Nevertheless, the comparison cases illustrate the potential accuracy of the
stereo camera system.

4.3.1 Radiosondes (Cases 1, 2, 5, 6)

During MAP, the best comparison data for low and middle clouds (< 8 km) were the frequent (every
3 h) radiosonde data from sondes launched only a few kilometers from the camera locations.
For example, comparison of the ground-based stereo images at 08/10/1999 10:58 UTC with the
Diepoldsau sounding launched at 11:00 UTC is shown in Figure 4.10. In the sounding emagram
the lowest cloud layer occurs from about 630 to 600 hPa, which corresponds to a height of 3.9 km
to 4.4 km above sea level. The CBH result from the stereo camera system is 3.96 ± 0.09 km. For
this case, the results from the ground-based stereo images correspond well with the lowest cloud
layer values from the sounding.

For cases 2, 5 and 6, the available soundings are plotted in Appendix A. On 13/10/1999 (case 2)
and 12/04/2002 (case 6), the clouds are too high (> 8 km) for a reliable CBH estimation from the
soundings. On 29/09/2001 (case 5), the sounding was launched about one hour after the
measurements. Comparing the humidity profile of the sounding with the consistent CBH results
of the skycam, IR camera and ceilometers (Table 4.7), the base of the lowest potential cloud layer
is significantly lower in the sounding, at about 2.3 km ASL.

4.3.2 LMD Transportable Wind Lidar (Case 3)

For the 20/10/1999 case comparison data from the LMD TWL Lidar were available. As Figure 4.11 shows, returns from the cirrus clouds were at an altitude between 9.0 km and 11.5 km ASL. The range-squared corrected backscatter signal, or RSCS, is an arbitrary unit that describes the level of reflectivity corrected for range. From the ground-based images taken at 20/10/1999 10:37 UTC a mean cloud height of 10.8 km and a height range between 9.2 and 12.0 km was retrieved. Unfortunately, the time difference between the measurements was about 30 minutes. Nevertheless, a general correspondence between the imager and lidar values can be reported for this case.

4.3.3 Ceilometers (Cases 4, 5, 6 and 7)

As shown above, the MAP radiosonde and Doppler lidar instruments allowed a first rough comparison of the ground-based stereo height retrievals with independent meteorological data. In the subsequent campaign at Zürich-Kloten our independent meteorological comparison data improved significantly with the location of the cameras in the vicinity of four Vaisala 25K ceilometers. These ceilometer data are currently the most accurate cloud-base height data available in Switzerland (Table 4.4).

For a quantitative comparison with the ceilometer point measurements, one has to know the exact cloud location that is retrieved by the ceilometer. As three of the four ceilometers are tilted, the x-/y-coordinates of the retrieved cloud locations are constantly changing with changes in cloud height. Therefore, we have concentrated our efforts on the data from the vertically pointing RW ceilometer which was located about a 4 m horizontal distance away from camera 2. The

Figure 4.11: Comparison of camera and lidar data. Left: Ground-based image at 20/10/1999 10:37 UTC; right: lidar time series plot of range-squared corrected backscatter signal (RSCS).
time series of cloud-base heights from the other three ceilometers were only used for qualitative comparisons with the stereo height retrievals.

The example considered in detail in this study consists of a 30 min CBH time series from 10:30 to 11:00 UTC on 19/04/2002 extracted from the ground-based image sequences and the RW ceilometer data. The camera images (Figure 4.12) show that there is a lower, broken stratocumulus layer with CBH values from 2.0-2.5 km ASL and a higher cirrus layer from 6-7 km ASL which is visible from time to time through the stratocumulus-free parts of the sky. Starting around 10:55 UTC, the stratocumulus formation has passed the field of view of the cameras and ceilometers (RW, HF), and only the cameras detect the higher cirrus layer in the last time step. In Figure 4.13 the corresponding ceilometer time series between 10:00 UTC and 12:00 UTC is plotted. While the upper cirrus layer is roughly detected with weak signal by the HF ceilometer, the RW ceilometer is only reporting low clouds (e.g. at 10:50 UTC) or clear sky (e.g. at 11:00 UTC). This result illustrates the difficulty of characterizing broken cloud situations by a single ceilometer, even when all the CBH values are within the measurement range of the ceilometer. A second problem for a ceilometer is, of course, high cirrus layers, or contrails, where clear sky is reported in most cases, as will be demonstrated below.

For quantitative comparisons of the time series between 10:30 UTC and 11:00 UTC, seven time intervals with a spacing of 5 min were analyzed (Table 4.6). The nearest 10 cloud points to the location of the RW ceilometer were extracted from the stereo CBH results and averaged. Except for the 10:55 UTC time interval, all points were from the same cloud layer, while at 10:55 UTC the points were grouped into two distinct layers. For the 15 s ceilometer data the values within a small window of ± 60 s (i.e. 9 values) were averaged. As the results in Table 4.6 illustrate, the stereo-derived CBHs are quite consistent with the ceilometer values.

Ceilometer detection of cloud structures with small horizontal extent is problematic. The time series plots from all four ceilometers on 27/09/2001 between 10:00 UTC and 11:00 UTC (Figure 4.14) show the rare cloud signals registered by the ceilometers, although the sky was continuously contaminated with contrails during the whole period. Second, the Vaisala 25K ceilometer data are only reliable up to a height of about 5-6 km. For the 12/04/2002 case with cloud-base heights of

Figure 4.12: Cloud situation, 19/04/2002. Left: at 10:50 UTC; right: at 11:00 UTC.
<table>
<thead>
<tr>
<th>Time</th>
<th>Camera system average, std dev. [m ASL]</th>
<th>Camera system theor. accuracy</th>
<th>Ceilometer, 2 min average, std dev. [m ASL]</th>
<th>Ceilometer theor. accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:30:00</td>
<td>2519 ± 9</td>
<td>10</td>
<td>2375 ± 42</td>
<td>48</td>
</tr>
<tr>
<td>10:35:00</td>
<td>2123 ± 114</td>
<td>7</td>
<td>2198 ± 205</td>
<td>44</td>
</tr>
<tr>
<td>10:40:00</td>
<td>2001 ± 3</td>
<td>6</td>
<td>1957 ± 16</td>
<td>39</td>
</tr>
<tr>
<td>10:45:00</td>
<td>2168 ± 88</td>
<td>7</td>
<td>2080 ± 56</td>
<td>42</td>
</tr>
<tr>
<td>10:50:00</td>
<td>2167 ± 114</td>
<td>7</td>
<td>2181 ± 181</td>
<td>44</td>
</tr>
<tr>
<td>10:55:00</td>
<td>2211 ± 63</td>
<td>8</td>
<td>2106 ± 33</td>
<td>42</td>
</tr>
<tr>
<td>11:00:00</td>
<td>5698 ± 114</td>
<td>49</td>
<td>- (clear sky)</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.6: Comparison with ceilometer time series data, 19/04/2002 10:30-11:00 UTC. The theoretical accuracy of the camera system is calculated according to Equation 2.2 with a parallax accuracy $s_{pa}$ of two pixels (= 2\(\times\)0.0075 mm), according to the accuracy of the orientation and the matching; the theoretical accuracy for the ceilometer is taken as 2% of CBH as given in the Vaisala product description (Vaisala, 2002).

Figure 4.13: RW and HF Ceilometer CBH time series on 19/04/2002. 1 = accurate cloud layer signal; 4 = noisy cloud layer signal.
around 10-11 km, the ceilometer could not be used as a comparison instrument. Ceilometer measurements are most accurate for low thick cloud layers, e.g. stratus, as in the 29/09/2001 case. The 2-minute average cloud-base heights for 29/09/2001 from all four ceilometers are listed in Table 4.7. Their retrieved height values correspond well with the heights retrieved by the IR camera and by our stereo camera system.

4.3.4 Infratec IR camera (Case 4, 5)

Thermal infrared cameras have the ability to measure the brightness temperature of an object, which provides information about cloud-base height. For an optically thick cloud with emissivity of 1.0 the cloud brightness temperature can be directly converted into an estimate of cloud height. For clouds with lower emissivities, the cloud brightness temperature and the cloud height are no longer tightly coupled and have to be adjusted, if a rough estimate of the emissivity is available.

<table>
<thead>
<tr>
<th>Camera system</th>
<th>Ceil RW CBH</th>
<th>Ceil HF CBH</th>
<th>Ceil MM CBH</th>
<th>Ceil BD CBH</th>
<th>IR camera CBH</th>
<th>IR camera CBT [K]</th>
<th>CBH</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBH [m ASL]</td>
<td>3487 ± 120</td>
<td>3455 ± 52</td>
<td>3524 ± 28</td>
<td>3463 ± 32</td>
<td>3494 ± 7</td>
<td>271.6 ± 0.5</td>
<td>3650 ± 80</td>
</tr>
</tbody>
</table>

Table 4.7: Stereo-derived CBH comparison with ceilometer heights and IR camera cloud-base temperature for 1308 UTC on 29/09/2001. Temperature values are converted to height values using data from the ETH sonde launched at 15:00 UTC.
We present two comparison cases, one with contrails (Figure 4.15), which can be assumed to have an emissivity < 1.0, and one with an optically thick stratus layer with emissivity ≈ 1.0.

The comparison results for the contrail case on 27/09/2001 (Table 4.8) show significant differences between the skycam and IR camera heights. There are three factors that can partly explain the large discrepancies. First, as mentioned above, an emissivity correction should be applied to the retrieved height values as these contrails are not behaving like a blackbody. Second, the recorded contrail temperatures are below the calibrated measurement range of the IR camera. Finally, the conversion from temperature to height had to be done with the Payerne sounding, which has a horizontal distance of about 150 km to Zürich-Kloten. Overall, this example demonstrates that contrail height retrieval with IR cameras is difficult and one must take into account different emissivity values for the various contrails.

The second comparison case is for a stratus situation at 13:08 UTC on 29/09/2001, with coincident skycam, IR camera, ceilometer and ETH sounding data. The results from each system are summarized in Table 4.7. In general, the agreement between the different data sources is good. The rather large standard deviations in the stereo camera system CBHs are caused by little texture throughout the image so that less points were extracted and a large number of them were not accurately matched. Such textureless stratus situations are certainly one of the most difficult cloud systems from which to successfully extract the cloud-base height field with our photogrammetric methods.

### 4.3.5 Summary of ground-based comparison cases

A summary of the results from all comparison cases, including the theoretical accuracies of each measurement method, is presented in Table 4.9. For each case, the mean cloud-base height and standard deviation within the region of interest is given, as derived from the stereo images. The region of interest within the multi-view camera images varies between a few square meters for the comparison with the ceilometer point measurements to the full overlap area of the cameras for the comparison with the LMD lidar, the radiosonde and the satellite-based results. The theoretical accuracy $s_z$ was calculated according to Equation 2.2 with a parallax accuracy $s_{px}$ of two pixels.
Figure 4.15: Comparison of a visible image from camera 1, zoomed (left) and a coincident IR camera image (right). Note the similarities between the visible and thermal infrared images.

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Stereo-based CBH mean [m ASL]</th>
<th>std.dev. [m]</th>
<th>theor. $s_z$ [m]</th>
<th>Comparison results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>08-10-1999</td>
<td>3960</td>
<td>90</td>
<td>15</td>
<td>Radiosonde:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>($\sigma_{\text{theor}} = 100\text{–}200\text{ m}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>630 hPa $= 3900 \text{ m}$</td>
</tr>
<tr>
<td>2</td>
<td>13-10-1999</td>
<td>Lower layer: 8'000</td>
<td>110</td>
<td>63</td>
<td>ATSR2, Meteosat-6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper layer: 10'900</td>
<td>130</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>20-10-1999</td>
<td>10'800</td>
<td>850</td>
<td>114</td>
<td>LMD lidar:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>($\sigma_{\text{theor}} \approx 200 \text{ m}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Range: 9'000 - 11'500 m</td>
</tr>
<tr>
<td>4</td>
<td>27-09-2001</td>
<td>Contrail 1: 8'500</td>
<td>100</td>
<td>109</td>
<td>IR camera:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contrail 2: 10'100</td>
<td>200</td>
<td>155</td>
<td>10'800 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contrail 3: 9'900</td>
<td>100</td>
<td>149</td>
<td>12'300 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10'900 m</td>
</tr>
<tr>
<td>5</td>
<td>29-09-2001</td>
<td>3487</td>
<td>120</td>
<td>18</td>
<td>IR camera:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3650 ± 80 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ceilometer:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>($\sigma_{\text{theor}} = 69 \text{ m}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3455 ± 52 m</td>
</tr>
<tr>
<td>6</td>
<td>12-04-2002</td>
<td>10'870</td>
<td>970</td>
<td>150</td>
<td>ASTER, MISR</td>
</tr>
<tr>
<td>7</td>
<td>19-04-2002</td>
<td>2'001</td>
<td>3</td>
<td>6</td>
<td>MISR</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>Ceilometer:</td>
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<td></td>
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<td>($\sigma_{\text{theor}} = 39 \text{ m}$)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1957 ± 16 m</td>
</tr>
</tbody>
</table>

Table 4.9: Overview of ground-based comparison results. The accuracy of the stereo camera system is calculated according to Equation 2.2, assuming a parallax accuracy $s_{\text{par}}$ of 2 pixels (matching and calibration/ orientation accuracy). The results of the comparison with satellite data (cases 2, 6 and 7) are shown in Chapter 6.
The parallax accuracy was estimated from the measurement accuracy $\sigma_M$ of about 0.5-1.0 pixels and from the accuracies of the two orientations $\sigma_{Ori1}$ and $\sigma_{Ori2}$ (angle accuracy of 40” results in a parallax accuracy for each $\sigma_{Ori}$ of about 1.0 pixel). In the last column, “comparison results”, the CBH results from the various comparison instruments are listed. The satellite-based results (cases 2, 6 and 7) are described in more detail in Chapter 6.
Chapter 5

Satellite-based analysis

Satellite-based stereoscopy of clouds has a long tradition in meteorology (Hasler, 1981). Stereo measurements have the advantage that they depend only on basic geometric relationships of observations of cloud features from at least two different viewing angles, while other cloud-top height estimation methods are dependent on knowledge of additional atmospheric parameters, like cloud emissivity, ambient temperature or lapse rate. Both geostationary and polar-orbiting satellite sensors can be used in a number of configurations for cloud stereoscopy, as described in Fujita (1982), Campbell and Holmlund (2000) and Yi et al. (2001). Over Europe, the following satellite configurations can currently be used for cloud stereoscopy: a single polar-orbiter with two views, such as ERS2-ATSR2, ENVISAT-AATSR and EOS Terra-ASTER, a single polar-orbiter with more than two views, such as EOS Terra-MISR, or two geostationary Meteosat satellites, such as Meteosat-6 and Meteosat-7. ASTER is only considered because the instrument is installed on the EOS-Terra platform as MISR. Multi-view satellites for cloud analysis should optimally have a spatial resolution of about 100 m. Further combinations, like a Meteosat satellite combined with another geostationary satellite (e.g. GOES-E) are not recommended due to the south-north scanning direction of the Meteosat satellites and the north-south scanning of all other geostationary satellites. The different scan directions increase the difficulty of matching and correcting for motion errors.

In contrast to stereo image pairs from geostationary satellites, if scan synchronized, and ground-based camera systems, stereo image pairs from a single polar-orbiting satellite are never perfectly synchronous. There is generally a time delay of several seconds to minutes between the image acquisition of the different viewing angles. While this is no problem for digital terrain model (DTM) generation of non-moving objects (e.g. land surface), it generates a height error in the stereo cloud-top height retrievals that can be quite large depending on the along-track cloud motion, as will be described in Section 5.2.2.
The three types of polar-orbiting multi-view instruments on board ERS-2 (i.e. ATSR2) and EOS-Terra (i.e. MISR and ASTER) to retrieve cloud-top height (CTH)/cloud-top wind (CTW) are quite different in their image acquisition, operational processing chain and how the data products are delivered. Therefore, the following sections give a short overview of each of the three multi-view sensors that we used in our study.

### 5.1 Description of sensors

The three types of polar-orbiting multi-view instruments on board ERS-2 (i.e. ATSR2) and EOS-Terra (i.e. MISR and ASTER) to retrieve cloud-top height (CTH)/cloud-top wind (CTW) are quite different in their image acquisition, operational processing chain and how the data products are delivered. Therefore, the following sections give a short overview of each of the three multi-view sensors that we used in our study.

#### 5.1.1 ATSR2

The Along Track Scanning Radiometer (ATSR2) instrument is part of the ERS-2 satellite system which was launched in April 1995. The successor sensor, AATSR, is part of Envisat which was recently launched in Spring 2002. ERS-2 is in a near-circular, sun-synchronous orbit at a mean height of 780 km, an inclination of 98.5° and a sub-satellite velocity of 6.7 km/s. The spacecraft is positioned to operate with a descending equator crossing time of around 10:30 local solar time and an ascending equator crossing time of 22:30 local solar time. The repeat cycle of ATSR2 is approximately 3 days.

The ATSR2 sensor first views the surface along the direction of the orbit track at an incidence angle of 55° as it flies toward the scene. Then, some 120 s later, ATSR2 records a second observation of the scene at an angle close to the nadir (Mutlow, 1999). The ATSR2 field of view is comprised of two 500 km-wide curved swaths with 555 pixels across the nadir swath and 371 pixels across the forward swath. The pixel size is 1 km x 1 km at the center of the nadir scan and 1.5 km x 2 km at the center of the forward scan. The sensor records in seven spectral channels, i.e. 0.55 µm, 0.67 µm, 0.87 µm, 1.6 µm, 3.7 µm, 10.8 µm and 12.0 µm, which is comparable to the channels of the new Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument on the
Meteosat Second Generation (MSG) platform. All channels have a radiometric resolution of 10-bit. Our cloud-top height retrieval from ATSR2 is based on the rectified data product (GBT) which was available in near-realtime from the ESA ATSR near-realtime service (Buongiorno, 1999). The geolocation for the GBT products proceeds by mapping the acquired pixels onto a 512 x 512 grid with 1 km pixel size whose axes are the ERS-2 satellite ground-track and great circles orthogonal to the ground-track. Georectification is performed with nearest neighbor resampling.

Several significant data quality problems can be found in the ATSR2 data; some of them are also reported in Danson et al. (1999). First, there are radiance differences between odd and even pixels. As Figure 5.2 of an enhanced ATSR2 nadir image from the 0.87 μm channel shows, the difference between odd and even pixels is obvious. The reason for the difference is that odd and even pixels from the sensor are calibrated separately, as they are obtained from different integrators (Chris Mutlow, personal communication). A second problem is scan jitter. The correct positional registration of the pixels around a scan relies on a steady scan rotation rate. When the rotation speed of the scan mirror deviates from the regular rotation rate, it results in a misalignment of data, or scan jitter, from successive scans (Mutlow, 1999) (Figure 5.2 right).

Since January 2000, attention has to be paid to the geolocation accuracy of the GBT product due to ATSR2 misregistration problems in mono-gyro mode (Accica and Goryl, 2002). In normal three-gyros yaw steering mode operation geolocation accuracy has been evaluated to be between 1 and 2 pixels. Since February 2001, following the loss of the gyroscopes, ERS-2 has been piloting using only one gyroscope, degrading the quality of the attitude pointing. Evaluation of the absolute geolocation by Accica and Goryl (2002) shows inaccuracies of the nadir image of up...
to 4-6 pixels (= 4-6 km). Due to these rectification errors, the geolocation accuracy of the nadir image was checked for all ATSR2 scenes in 2000 and 2001 with semi-automatically measured tie points in the ATSR2 nadir image and the geolocated MISR nadir (AN) image. For the tie point measurements, the second pyramid level of MISR data (spatial resolution of $2^2 \times 275$ m = 1100 m) and the original level of ATSR2 data (spatial resolution of 1000 m) were used (Figure 5.3). For the 13/06/2001 case with the extremely large relative deviations due to the mono-gyro mode, the absolute geolocation errors are also on the order of the maximum shifts described in Accica and Goryl (2002). Fortunately, the errors around Chilbolton, UK (51.14 N, 1.44 W) are even only 1-2 pixels in the x- and y-directions.

Next to the absolute geolocation accuracy of the nadir image, the accuracy of the relative geolocation between the nadir and forward images is very important for precise stereo CTH results. This relative accuracy can be checked with a set of semi-automatically measured tie points at coast lines. The mean along- ($\Delta x$) and cross-track ($\Delta y$) shifts for the three ATSR2 scenes used in the case studies are presented in Table 5.2. Smaller data problems found in some ATSR2 data sets (e.g. 03-08-2000) are missing image lines or “zero pixels” with an error code. These lines and pixels are filled in our preprocessing by interpolation from neighboring pixels.

For the CTH calculation from the along-track parallax between nadir and forward views (Equation 5.3), the zenith angles and the relative acquisition time between the views for the motion correction

<table>
<thead>
<tr>
<th>Date</th>
<th>Cross-track shift $\Delta x$ [pixels]</th>
<th>Along-track shift $\Delta y$ [pixels]</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-06-2000</td>
<td>0.5</td>
<td>-3.2</td>
</tr>
<tr>
<td>03-08-2000</td>
<td>1.6</td>
<td>3.5</td>
</tr>
<tr>
<td>13-06-2001</td>
<td>105.0</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 5.2: Relative geolocation accuracy between ATSR2 nadir and forward views. The large shift in cross-track direction in the third case is caused due to the mono-gyro mode of ERS-2.
are needed. The nadir and forward zenith angles are known at 11 equally distributed points across the first and last scan line from the GBT header and can be linearly interpolated to all pixels (Bailey, 1995). The exact time difference between the same pixel in the forward and nadir scans is calculated from the along-track ground distance and the satellite velocity.

5.1.2 MISR

The Multi-angle Imaging SpectroRadiometer (MISR) is currently the only operational satellite to offer multi-view stereo images. MISR was launched on board the EOS AM-1 Terra spacecraft in December 1999 (MISR, 2002b). The orbit is sun-synchronous at a mean height of 705 km with an inclination of 98.5° and an equatorial crossing time of about 10:30 local solar time. The repeat cycle is 16 days. The MISR instrument consists of nine pushbroom cameras at different viewing angles: -70.5° (named DA), -60.0° (CA), -45.6° (BA), -26.1° (AA), 0.0° (AN), 26.1° (AF), 45.6° (BF), 60.0° (CF), and 70.5° (DF). The time delay between adjacent camera views is 45-60 seconds which results in a total delay between the DA and DF images of about 7 minutes. The four MISR spectral bands are centered at 446 nm (blue), 558 nm (green), 672 nm (red) and 866 nm (NIR). The red-band data from all nine cameras and all spectral bands of the nadir camera are saved in high-resolution with a pixel size of 275 m x 275 m. The data of the blue, green and NIR bands of the remaining eight non-nadir cameras are stored in low-resolution with a pixel size of 1.1 km x 1.1 km. The operational data products from MISR are described in Lewicki et al. (1999). The two products used for this study are the L1B2 ellipsoid-projected radiance data product and the L2TC top-of-atmosphere/ cloud product.
The L1B2 ellipsoid-projected radiance product is referenced to the surface of the WGS84 ellipsoid with no terrain elevation included. The Space Oblique Mercator (SOM) projection (Snyder, 1987) was selected as the reference map grid because it is specifically suited for continuous mapping of satellite imagery. The y-direction, called "X", follows approximately the direction of the satellite groundtrack motion, with the "Y" axis perpendicular to it. Over Europe, the SOM grid is rotated about 12° clockwise (CW) against geographical North (Figure 5.5 right). The tilt angle is slowly changing along the swath and between cameras, but it can be assumed constant over several blocks (Veliko Jovanovic, personal communication). The geographical coordinates of the SOM grid points are given for each path in the Ancillary Geographic Product (AGP) at a 1.1 km x 1.1 km resolution (ATBD-5, Lewicki and Zong 1999). For data deliveries after georectification (> L1B1), each MISR path is cut up into a series of pre-defined, uniformly-sized SOM boxes along the ground track, so called “blocks”. The principle of the block structure of the MISR data products is briefly illustrated in Figure 5.5 and explained in Bothwell et al. (2002).

The MISR georectified product spatial horizontal accuracy requirements are driven by the needs of the geophysical parameter retrieval algorithms. The goal of operational MISR data processing is to achieve an uncertainty better than ± 140 m for both the absolute geolocation of the nadir
camera and the coregistration between all nine cameras (Jovanovic et al., 2002). The detailed theory on the georectification algorithms and the in-flight camera geometric model (CGM) calibration is described in ATBD-3 (Jovanovic et al., 1999a) and ATBD-4 (Jovanovic et al., 1999b). Every few months since launch, the CGM version has been updated and the achieved accuracy of each of these versions is reported on the MISR georectification webpage (MISR, 2002a). For our five MISR scenes the following CGM versions were used at the NASA Langley Distributed Active Archive Center (DAAC) for the georectification: 28/06/2000 => CGM version 7; 03/08/2000 => CGM version 5; 13/06/2001 => CGM version 6; 12/04/2002 => CGM version 6; 19/04/2002 => CGM version 7. While CGM versions 2 to 4 had large coregistration errors of more than 1000 m between the nadir and B cameras and of more than 3000 m between the nadir and D cameras, CGM version 5 reported geolocation errors of less than 275 m, or 1 pixel, for all cameras, except the D cameras, as a result of the first full calibration using ground-control points. The imperfections in the georectification for the D cameras were sometimes visible as rotation errors in these most oblique viewing angles. However, a matching test on one of our scenes, which had been processed with CGM version 5, did not show any rotation errors (Figure 5.6). The latest evaluation results for CGM versions 6 and 7 shown in Jovanovic et al. (2002) are approaching prelaunch requirements, with along- and cross-track errors far below 1 pixel for all cameras. A further evaluation of the georectification procedure of MISR will be done in another ongoing study at our Institute concerning general sensor models for air- and space-borne linear array sensors (Poli, 2002).

As the MISR red channel is, in general, the only spectral channel with full resolution in all nine views, multi-spectral matching differences within multi-layer clouds, as for ATSR2, cannot be generated with MISR, at least not at the 275 m resolution. Matching tests with ATSR2 showed that the main differences in the cloud-height results occur between the visible and the thermal infrared channels, while the differences between visible channels or between infrared channels are small (Section 5.2.1). To check if the relative geolocation of the four spectral bands is actually within ±
50 m as stated in Jovanovic et al. (2002), cloud points were semi-automatically matched between the four spectral channels (Figure 5.7). The results listed in Table 5.3 confirm the high accuracy relative geolocation of the spectral channels, except some larger deviations with the green channel, as well as the maximum achievable subpixel accuracy of our least-squares matching algorithm in the MISR cloud matching of about $\pm 0.1$ pixels, or $\pm 28$ m.

All of our CTH and CTW calculations presented in this study fully rely on the L1B2 georectified radiance data. Only for identification of the exact acquisition time of each pixel the L1B2 SOM grid location has to be back-projected to the original line/pixel position within the MISR swath, which can be done with the transformation parameters stored in the L1B2 ancillary data. Due to the analytically defined surface of the ellipsoid with no topographic distortion the transformation between image space and map projection space can be modeled with the following elements: 1) satellite navigation, 2) camera geometry, 3) earth rotation, and 4) ellipsoid curvature. The mapping of SOM to image space is then given by the following approximate equations (Jovanovic et al., 1999a):

$$
\begin{align*}
    l &= c_1 + c_2 \Delta l_{som} + c_3 \Delta p_{som}^2 + c_4 \Delta p_{som} + c_5 \Delta l_{som} \Delta p_{som} + c_6 \Delta p_{som}^3 \\
    p &= d_1 + d_2 \Delta l_{som} + d_3 \Delta p_{som}^2 + d_4 \Delta p_{som} + d_5 \Delta l_{som} \Delta p_{som} + d_6 \Delta p_{som}^3.
\end{align*}
$$

(5.1)

where $\Delta l_{som} = l_{som} - (l_0)_{som}$ and $\Delta p_{som} = p_{som} - (p_0)_{som}$ are the line and column offset to the

<table>
<thead>
<tr>
<th></th>
<th>red - blue</th>
<th>red - green</th>
<th>red - nir</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross-track (dx)</td>
<td>-0.048 ± 0.042</td>
<td>-0.087 ± 0.133</td>
<td>-0.022 ± 0.055</td>
</tr>
<tr>
<td>along-track (dy)</td>
<td>-0.056 ± 0.038</td>
<td>-0.174 ± 0.053</td>
<td>-0.114 ± 0.043</td>
</tr>
</tbody>
</table>

Table 5.3: Relative accuracy between MISR spectral channels (in pixels).
first SOM grid element. For an orbit of SOM-projected data, a starting time $t_0$ for the orbit and a set of ellipsoid transform coefficients, $c_1$ to $c_6$ and $d_1$ to $d_6$, for the red band of each camera are provided in the L1B2 data. The starting time $t_0$ is the imaging time of the first SOM grid element $(l_0, p_0)_{som}$ in the current strip in Coordinated Universal Time (UTC). The ellipsoid transform maps each high resolution grid center $(l, p)_{som}$ into line and sample of MISR red band imagery $(l, p)$. The imaging time of the SOM grid point $(l, p)_{som}$ is given by Diner et al. (1999b):

$$t_{l, p} = t_0 + 0.0408(l - l_0),$$

(5.2)

where 0.0408 second is the image line repeat time and $l_0$ is the image line corresponding to the first grid element $(l_0, p_0)_{som}$.

Finally, the exact view zenith angles for each camera, which are needed for the CTH calculation, are available in the geometric parameters (GP) product, which supplies the sun and view zenith angles on the WGS84 ellipsoid relative to a normal to that surface, as well as azimuth angles relative to local North. These angles are reported on a grid with 17.6 km spacings. The sun zenith and azimuth angles are determined from Earth and Sun ephemerides at the time of viewing. The view zenith and azimuth angles are based upon the reported spacecraft attitude and position and the calibrated camera model.

The L2TC product contains the operationally derived cloud parameters, like stereo CTH, east-west (EW) and north-south (NS) cloud motion components, as well as many additional parameters from the stereo retrieval (Diner et al., 1999b). The operational matching algorithms and strategies of the MISR team for the L2TC CTH/CTW retrieval are described in Section 5.3 below.

### 5.1.3 ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an advanced multispectral imager that was launched, as MISR, on board the NASA-Terra spacecraft in December 1999 (ASTER, 2002a). ASTER covers a wide spectral region with 14 bands from the visible to the thermal infrared with high spatial, spectral and radiometric resolution. An additional backward-looking near infrared band provides stereo coverage. The sensor consists of three separate instrument subsystems. The Visible and Near Infrared (VNIR) subsystem has three bands with a spatial resolution of 15 m (named 1, 2, 3N) and an additional backward telescope for stereo (named 3B), the Shortwave Infrared (SWIR) has 6 bands with a spatial resolution of 30 m and the Thermal Infrared (TIR) has 5 bands with a spatial resolution of 90 m. Each ASTER scene covers an area of 60 km x 60 km. The VNIR subsystem, which provided the 3N/3B stereo images, consists of two independent telescope assemblies in the backward and nadir view directions to minimize image distortion (Figure 5.8).

In contrast to all other sensors on EOS-Terra (e.g. MISR, MODIS), ASTER is not acquiring data continuously due to the huge amount of data it generates, but only on specific dates/orbits or on demand. For cloud studies in coincidence with our ground-based imager system it was necessary
to order an ASTER image acquisition as the probability of an automatic ASTER image being coincident with our ground-based system was practically zero, as the ASTER field of view only includes Zuerich-Kloten airport twice (paths 194 and 195) within the 16 day repeat cycle. On-demand scheduling of satellite image acquisition is a rather challenging exercise. There are many parameters that can prevent a successful delivery of a scene, e.g. conflicting demands with different priorities, wrong scheduling, transmission failures, etc. In our case the task was even a little bit more complicated. While most of the ASTER demands are for land applications with minimal cloud cover, our application was dependent on there being some clouds within the ASTER images over Zuerich-Kloten. The on-demand orders had to be submitted to the ASTER ARO Office in Japan at least two months in advance of the field campaign. A total of 8 dates within three separate campaigns during September 2001, November 2001 and April 2002 were finally submitted and only one acquisition on 12/04/2002 succeeded with coincident ground-based measurements. The other seven dates failed due to “no clouds”, “fog”, “rain”, “cancelled” or “failed” image acquisition. Interestingly, the 12/04/2002 data set was not processable by the operational software at the ASTER processing center, probably due to the large cloud cover that prevented use of the automatic georectification routines that search for a set of predefined GCPs. In the end, the data were processed offline to the required L1B data product.

The stereo configuration of ASTER is illustrated in Figure 5.9 (Lang and Welch, 1999). The relation between the base-to-height ratio B/H and $\alpha$ is $B/H = \tan \alpha$, where $\alpha$ is the angle between the nadir and backward viewing directions at an observing point on the Earth surface. The angle $\alpha$ that corresponds to a B/H ratio of 0.6 is 30.96°. Considering the curvature of the Earth surface, the setting angle between the nadir and backward telescopes is designed to be 27.60°. A time lag of about 55 s occurs between the acquisition of the nadir and backward images.
The ASTER Level 1B data are L1A data with the radiometric and geometric coefficients applied to them. All of these data are stored together with metadata in one HDF file. The L1B image is projected onto a rotated map (rotated to “path oriented” coordinates) at full instrument resolution, which is 15 m for the received 3N/3B VNIR image data. The VNIR data have only 8-bit radiometric resolution.

Geolocation accuracy was checked with 20 ground control points around the “Zugersee”, “Baldeggersee” and “Halwylersee”. The GCPs were measured manually in the Swiss national map 1:25000 with an accuracy of about 10 m in X and Y and a height accuracy of 5 m. As the ASTER DEM algorithms work with ground control points, no exact zenith angles, as in the case of MISR, are given as ancillary data. Therefore, one has to either use the nominal height factor (i.e. base-to-height ratio B/H) of 0.6 or estimate the height factor with own ground control points. Using the heights of the 20 GCPs, the height factor was calculated to be 0.5945, by forcing the mean difference between the GCP and ASTER heights to 0.0 m. The standard deviation between the GCP and ASTER heights was 5.1 m, which confirms the 5 m a priori measurement accuracy of the GCPs. The mean difference and standard deviation between the GCP coordinates and the ASTER pixel coordinates, as interpolated from the header file, were -3.5 m and 22.4 m in the X direction and -0.7 and 27.2 m in the Y direction. Consequently, there was no significant systematic error in the ASTER georeferencing and the ASTER images were geolocated with an accuracy of at least 2 pixels, or 30 m. So, with the ASTER data simultaneous to MISR, we have a reference data set for cloud-top height retrieval with about 5 times better accuracy than MISR (i.e. 30 m
versus 140 m). Similar points between MISR and ASTER can be found by matching of the 4th pyramid level of ASTER (resolution: $2^4 \times 15$ m = 240 m) and the original level of MISR (resolution: 275 m) (Figure 5.10).

The exact acquisition time of the ASTER 3N and 3B data is given in an ancillary field of the HDF file. The times are saved about once every 100 ms and are given in the specific “Spacecraft Time Format” described in ASTER (2002b). The Spacecraft Time Code consists of four continuous time segments, each 16-bit in length, describing the “days since 1 January 1958”, “milliseconds of day (first part, to be multiplied with $2^{16}-1$)”, “milliseconds of day (second part)” and “microseconds of millisecond”.

5.1.4 METEOSAT

In this section, the data characteristics of three Meteosat configurations, 1) Meteosat-7 operational 30-minute scans, 2) Meteosat-6 5-minute rapid scans during MAP and 3) Meteosat-6 10-minute rapid scans since August 2000 are described (Table 5.4). The Meteosat geostationary image sequences are used as auxiliary data in this study, either to correct cloud-top heights from non-synchronous stereo pairs (Section 5.2.2) or to validate cloud motion retrievals from MISR (Section 5.4). In Section 5.2.4 we will shortly outline why the two current Meteosat systems cannot used themselves for stereo cloud-top height retrievals with acceptable accuracy.
Table 5.4: Characteristics of the Meteosat satellites that we used in this study. Meteosat-7, Meteosat-6 during MAP and Meteosat-6 Rapid Scan Service (RSS). All satellites acquire data in the same three spectral channels (VIS/WV/IR). The spatial resolutions of the visible (VIS) and infrared (IR)/water vapor (WV) channels are 2.5 km x 2.5 km and 5 km x 5 km, respectively, at the equator with decreasing y-resolution towards the poles. Over Switzerland (47° N), the pixel size is approximately 2.5 km x 4 km for the VIS channel and 5 km x 8 km for the IR/WV channels.

<table>
<thead>
<tr>
<th></th>
<th>Meteosat-7</th>
<th>Meteosat-6 MAP</th>
<th>Meteosat-6 RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resolution</td>
<td>30 min</td>
<td>5 min</td>
<td>10 min</td>
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<tr>
<td>Flying height</td>
<td>36'000 km</td>
<td>36'000 km</td>
<td>36'000 km</td>
</tr>
<tr>
<td>Longitude</td>
<td>0°</td>
<td>9° W</td>
<td>9° W</td>
</tr>
<tr>
<td>Starting line (VIS)</td>
<td>0</td>
<td>4218</td>
<td>2947</td>
</tr>
<tr>
<td>Time offset to M7</td>
<td>-</td>
<td>1:05 min</td>
<td>4:44 min</td>
</tr>
</tbody>
</table>

5.1.4.1 Meteosat-6 5-minute Rapid Scans during MAP

EUMETSAT supported the MAP experiment by implementing 5-minute rapid scans of the Alpine region (Figure 5.11) with the in-orbit stand-by Meteosat-6 positioned at 9° W (EUMETSAT, 2002). The limited scan starts at line 4218, or line 2109 for IR/WV, of the operational Meteosat-7 scan, which results in a time difference between the two scans of 1:05 minutes. The cloud motion from one rapid scan image to the next is in the range of 0-5 pixels. As image features, even clouds, are self-similar within these 5 minutes, tracking of cloud points is much easier compared to tracking of clouds in the operational 30-minute Meteosat-7 series where it can be difficult to select stable cloud tracers (Schmetz et al., 1993). Before application of the cloud tracking algorithms, the images were processed with a Wallis filter for contrast enhancement. Corresponding points in the image sequence were then automatically determined with our MPGC least-squares matching algorithm.

5.1.4.2 Meteosat-6 10-minute Rapid Scans

Following the success of the 5-minute Rapid Scanning support provided to MAP in autumn 1999, new 10-minute Rapid Scans were started by EUMETSAT in August 2000. These new trial scans normally had a duration of 48 to 72 hours a week. Since September 2001, an operational 10-minute Rapid Scanning Service (RSS) has been maintained by EUMETSAT (2002). For the rapid scans the in-orbit stand-by Meteosat-6 instrument, positioned at 9° W, is used. The limited

Figure 5.11: Meteosat-6 5-minute scan area during MAP.
scan consists of 5000 x 1666 pixels for the VIS channel and 2500 x 833 pixels for the IR/WV channels, starts at line 2947 for VIS and line 1474 for IR/WV of the operational Meteosat-7 scan and covers an area approximately from 10° N to 70° N (Figure 5.12). The time difference between Meteosat-6 and Meteosat-7 scans in this configuration is about 5 minutes. Again, the images were preprocessed with a Wallis filter for contrast enhancement and corresponding points in the image sequence were retrieved with our MPGC LSM algorithm. Because of the larger disparities (up to about 10 pixels) compared with the 5-minute MAP Rapid Scans, two pyramid levels (original and 1st pyramid level) were used in the matching. As image features, even clouds, are still self-similar at this resolution within the 10 minutes, tracking of cloud points is still possible with high reliability.

5.1.4.3 Meteosat-7

The operational European meteorological geostationary satellite, Meteosat-7, is located at 0° longitude. The whole scan consists of 5000 x 5000 VIS pixels and 2500 x 2500 IR/WV pixels. The image sequences of Meteosat-7 can also be used for cloud motion error corrections. However, with the 30-minute scans there is increased difficulty in assigning the Meteosat cloud motion to the corresponding cloud objects within the ATSR2/MISR/ASTER stereo pairs. Furthermore, cloud tracking is more difficult as the shape of the clouds can change significantly within the 30-minute interval. As for the 5- and 10-minutes Rapid Scans, the images were preprocessed with a Wallis filter for contrast enhancement and corresponding points in the image sequence were then determined with the MPGC LSM algorithm. Because of the larger disparities (up to about 30 pixels) compared with the Meteosat-6 Rapid Scans, four pyramid levels (original, 1st, 2nd and 3rd pyramid levels) were used in the matching.

5.2 Determination of CTH and CTW

Determination of CTH from ATSR2, ASTER or any two views of MISR proceeds along the same scheme (Figure 5.13). The scheme is approximately the same as for the ground-based images.
(Figure 4.1), except that the calculated CTH values have to be corrected for height errors introduced by cloud motion within the time delay of the acquisition of the two views. The second substantial difference between the two processing schemes is the use of the exact orientation parameters as geometric constraints in the case of the ground-based images, while for the satellite-based images, no geometric constraints have been used to date. We plan to include geometric constraints in the MISR matching as soon as the necessary orientation parameters are available from the processing of the MISR L1B1 images with a new general sensor model for linear array sensors (Poli, 2002).

First, all images were reduced to 8-bit with linear stretching between the minimum and maximum values and 0.5% of the extreme values in both tails of the histogram were removed, excluding the pixels assigned an error code. As no a priori values of the cloud heights were given to the matching algorithm, the number of pyramid levels for the hierarchical matching was chosen so that the maximum possible parallax at the highest level was only 1-2 pixels. Three, five and seven pyramid levels were used for ATSR2, MISR and ASTER, respectively. Every pyramid level was enhanced and radiometrically equalized with the Wallis filter. According to the block or filter size (see Section 3.1), different cloud structures can be enhanced. In general, a block size of about 70 was chosen at the original level, which was then decreased up the pyramid. Points with good texture were selected with the Förstner or Harris interest operator in the first or second pyramid level because it is likely that these same points are readily detectable in the other levels. In Figure 5.14 the Harris point distribution for one MISR block is shown. Due to the preprocessing with the Wallis filter, the point distribution is more regular and a sufficient number of points is also extracted in regions with little texture (e.g. within clouds). If a cloud mask was available (e.g. our own cloud mask for ATSR2, L1 RCCM or L2TC cloud masks for MISR), we used it for thinning of the point set to cloud points only, prior to matching.

The unconstrained MPGC LSM matching is applied hierarchically, starting on the highest pyramid
level. After each pyramid level, quality control with absolute tests on the LSM matching statistics is performed to exclude the largest blunders from further processing down the pyramid. The patch size is slightly increased from one pyramid level to the next, from $7 \times 7$ on the highest level to about $15 \times 15$ on the lowest level.

After applying the cloud-adapted matching algorithm, the matching solutions are quality-controlled with absolute and relative tests on the matching statistics, as described in Chapter 3. The quality codes can be used for color-coding of the matched points, providing visual quality control of both matching quality and the effectiveness of the quality control tests (Figure 5.15). Additionally, meteorological criteria can be used in the detection of large blunders, including minimum and maximum cloud heights, minimum and maximum cross-track parallaxes, which are, after division by the time difference, proportional to the cross-track wind speed, or filtering the cloud heights with the brightness temperature values from the IR channel(s) in the case of ATSR2. For the case studies shown in this work, we never applied these additional criteria.

The resulting $y$-parallaxes $y_p$ are converted into cloud-top heights ($cth$) as (Fujita 1982; Prata and Turner 1997)

$$
cth = \frac{y_p}{\tan(\theta_{\text{forward}}} - \tan(\theta_{\text{nadir}})}
$$

(5.3)

where the zenith angles $\theta_{\text{forward}}$ and $\theta_{\text{nadir}}$ have to be projected on the along-track plane. The height values of the successfully matched points are finally interpolated to the full resolution grid.

The accuracy of the retrieved cloud-top heights is dependent on the geometric stereo configura-
tion expressed as the base-to-height ratio $B/H$, on the matching accuracy ($\Delta y_p$), on the accuracy of the georectification, including the exact values of the zenith angles, and on the along-track motion retrieval accuracy ($\Delta v'$). In Table 5.5 the $B/H$ values and image time differences for ATSR2, ASTER and different viewing angle combinations of MISR are listed, together with an estimation of the height error $\Delta h$ given an along-track parallax error $\Delta y_p$ of 1 pixel from georectification or matching or an along-track motion error $\Delta v'$ of 5 m/s:

$$\Delta h = \frac{\Delta y_p}{(B/H)} \times \text{pixel size},$$

(5.4)

and

$$\Delta h = \frac{\Delta v' \times \Delta t}{(B/H)}.$$  

(5.5)

For all sensors the height error due to motion errors is very prominent. Interestingly, for most of the listed configurations the motion-induced error is about the same magnitude. So, for example, a relative cloud height comparison between MISR AN_AF and ASTER is possible on the accuracy level given by the georectification accuracy, i.e. $30$ m versus $140$ m. Moreover, while a theoretical cloud height accuracy of $25$ m can be obtained from ASTER with one pixel parallax accuracy, the same absolute accuracy would require an along-track motion retrieval accuracy of better than $0.3$ m/s, which is currently impossible to achieve with cloud tracking in coarse resolution geostationary satellite images. A summary of cloud motion correction methods is presented in Sections 5.2.2 and 5.2.3.
The spectral characteristics of clouds are largely dependent on the phase (i.e. liquid, ice) of the cloud particles, the size and shape of the cloud particles and the liquid, or ice, water content of the cloud. The optical depths of clouds vary significantly within the electromagnetic spectrum. In the microwave region they are much smaller than in the visible and infrared parts. ATSR2, with its seven spectral stereo channels, provides a useful data base for the study of spectral differences in stereo cloud-top height retrievals. A detailed review of multi-spectral cloud parameter retrieval from ATSR2 and, in the near future, from SEVIRI on board Meteosat Second Generation (MSG) is given in Watts et al. (1998). Differences in the ATSR2 stereo matching results between various spectral channels are mainly seen between the group of VIS/NIR channels (0.55 $\mu$m, 0.67 $\mu$m, 0.87 $\mu$m) and the group of IR channels (11.0 $\mu$m, 12.0 $\mu$m), mostly in cases of optically thick clouds under thin cirrus.

For example, consider the cloud situation over Eastern Switzerland, Austria and Northern Italy on the 13th October 1999 (Figure 5.16). The spectral differences in the CTH results are presented in Figure 5.17. The CTH differences are mainly observable in the upper part of the image, where there is a low optically thick valley fog layer with very high thin cirrus bands above. In the Adria region (lower right) one can also see that the semi-transparent cloud structures over the sea were not detected by the stereo matching in the visible channel.

### 5.2.1 Differences between spectral channels

The spectral characteristics of clouds are largely dependent on the phase (i.e. liquid, ice) of the cloud particles, the size and shape of the cloud particles and the liquid, or ice, water content of the cloud. The optical depths of clouds vary significantly within the electromagnetic spectrum. In the microwave region they are much smaller than in the visible and infrared parts. ATSR2, with its seven spectral stereo channels, provides a useful data base for the study of spectral differences in stereo cloud-top height retrievals. A detailed review of multi-spectral cloud parameter retrieval from ATSR2 and, in the near future, from SEVIRI on board Meteosat Second Generation (MSG) is given in Watts et al. (1998). Differences in the ATSR2 stereo matching results between various spectral channels are mainly seen between the group of VIS/NIR channels (0.55 $\mu$m, 0.67 $\mu$m, 0.87 $\mu$m) and the group of IR channels (11.0 $\mu$m, 12.0 $\mu$m), mostly in cases of optically thick clouds under thin cirrus.

For example, consider the cloud situation over Eastern Switzerland, Austria and Northern Italy on the 13th October 1999 (Figure 5.16). The spectral differences in the CTH results are presented in Figure 5.17. The CTH differences are mainly observable in the upper part of the image, where there is a low optically thick valley fog layer with very high thin cirrus bands above. In the Adria region (lower right) one can also see that the semi-transparent cloud structures over the sea were not detected by the stereo matching in the visible channel.

### 5.2.2 Cloud-top wind retrievals and stereo CTH corrections

In contrast to stereo image pairs from scan-synchronized geostationary satellites, stereo image pairs from a single polar-orbiting satellite are never perfectly synchronous. There is a time delay of
Figure 5.16: ATSR2 scene on 13/10/1999. Left: false-colour composite image of channels 1.6-0.87-0.55 μm, with rectangles indicating the regions with the largest spectral differences in the stereo height retrievals (see Figure 5.17); right: anaglyph image rotated by 90° CCW, which can be viewed with red-green glasses (red = right eye).

Figure 5.17: CTH results on 13/10/1999 from ATSR2. Left: from 0.87 μm channel; right: from 11.0 μm channel. The largest differences are indicated with the two rectangles: in the upper left corner (red rectangle), the VIS results show a low stratus layer while the higher cirrus layer is mapped in the IR results; in the bottom right corner (yellow rectangle), the clouds over the Adriatic Sea are only recognized in the IR channel.
seconds to minutes between image acquisition at the different viewing angles. The resulting errors in stereo cloud-top height retrievals can be quite large, depending on the along-track cloud motion, as is pointed out in Table 5.5. If more than two non-symmetric views are available, the along-track parallax can be separated into the amount due to cloud height and the amount due to cloud motion (Section 5.2.3). With only two views, or symmetric multiple views, which is the usually the case, the along-track cloud motion has to be corrected with data from an independent source.

One possible source of independent data is geostationary satellite cloud motion information. In our study three types of geostationary data from the two European satellites Meteosat-6 and Meteosat-7 were used (Section 5.1.4): the Meteosat-6 5-minute Rapid Scans during MAP, the quasi-operational Meteosat-6 10-minute Rapid Scans and the operational Meteosat-7 30-minute sequences.

Given no time delay between stereo image pair acquisition, the following relationships are satisfied for a satellite-based stereo pair, according to Equation 5.3:

\[
\begin{align*}
x_p &= 0, \\
y_p &= f(c th, \theta_1, \theta_2),
\end{align*}
\]

where \(x_p\) is the cross-track parallax, \(y_p\) is the along-track parallax, \(c th\) is the cloud-top height and \(\theta_1\) and \(\theta_2\) are the viewing zenith angles.

Considering time delay and cloud motion, Equations 5.6 have to be modified as

\[
\begin{align*}
x_p &= f(u', \Delta t), \\
y_p &= f(c th, \theta_1, \theta_2, u', \Delta t),
\end{align*}
\]

where \((u', v')\) are the cross-track and along-track wind components. As the satellite ground paths

---

**Figure 5.18:** Time delay between acquisition of the ATSR2 forward and nadir images as a function of the cross-track distance.
are not exactly aligned with geographical North (over Europe the tilt angle is around 12° for MISR and 14° for ATSR2), \((u', v')\) have to be rotated to be comparable with the standard E-W wind component \(u\) and N-S component \(v\).

For cross-track wind retrieval and along-track wind correction, the exact time difference \(\Delta t\) between corresponding pixels in the forward and nadir scans has to be calculated. For ATSR2 the time difference (see Figure 5.18) varies significantly over the scan and can be calculated from the along-track distance on the ground and the satellite velocity after Lorenz (1985). For MISR and ASTER the time difference for different cross-track positions within a block or scene can be assumed as constant. Northerly winds lead to an underestimation of the heights and the along-track wind component has to be added to the \(y\)-parallax, while southerly winds result in overestimation of cloud-top heights. The motion vectors retrieved from Meteosat-6 and Meteosat-7 data, as described in Section 5.1.4, were resampled to the ATSR2/MISR/ASTER grid and the cross- and along-track wind components calculated (e.g. Figure 5.19). Using the time difference between the acquisition of the two views, the along-track wind components are converted into CTH corrections.

### 5.2.3 Simultaneous CTH and CTW retrieval

As an alternative to the logistically difficult problem of a tandem mission of two polar-orbiting satellites to get synchronous high-resolution stereo images, the use of at least three non-symmetric views from a single polar-orbiting satellite can solve the issue of cloud motion errors in satellite-based stereo CTH retrievals, as this configuration allows the simultaneous estimation of CTH and CTW. The only currently operational satellite to offer such multi-view stereo images is MISR (Section 5.1.2). With three geolocated views, Equations 5.6 can be extended to the following linear equation system with four equations and three unknowns \((u', v'\) and \(c_{\text{th}})\):
where \((x_p)_{1,2}, (y_p)_{1,2}\) are the x-/y-parallaxes between views 1 and 2 and \((x_p)_{2,3}, (y_p)_{2,3}\) are the x-/y-parallaxes between views 2 and 3. The equation system is based on the assumption that there is no change of \(c\) and \(\theta\) within the time interval \(t_1\) to \(t_3\). Equations 5.8a and 5.8c can be easily solved for the cross-track motion component \(u'\) with known acquisition times \(t_1\), \(t_2\) and \(t_3\). The separability of \(c\) and \(\theta\) in Equations 5.8b and 5.8d can be described with the determinant

\[
D = (\tan(\theta_1) - \tan(\theta_2))(t_3 - t_2) - (\tan(\theta_2) - \tan(\theta_3))(t_2 - t_1). \tag{5.9}
\]

According to the magnitude of the determinants of each MISR triplet combination as listed in Horvath and Davies (2001), the best separability is achieved with the triplet DF-BF-CA/DA-BA-CF. However, the meteorological assumption of constant CTH and CTW within the triplet acquisition period is hardly fulfilled, even at the MISR resolution, for this triplet combination with a time span of about 6 minutes between the DA and CF cameras. The triplet with the smallest time span of 92 s, AN-AF-BF/AN-AA-BA, has a very low determinant value that results in noisy CTH and CTW values. A second point to consider is the cloud matching. Especially between non-adjacent cameras, matching is more difficult due to shape changes and appearance/disappearance of cloud features (Figure 5.20). These problems are comparable to the ground-based tracking problems reported in Section 4.1.4. In particular, the DF view is quite difficult to match with the other views (Table 5.6).

One approach for potentially improving the success rate of matching towards the more oblique viewing angles is illustrated in Figure 5.21. Instead of matching from AN to DF directly, matching is started with the AN-AF stereo pair. The results are then extrapolated as new approximate starting values for matching in the AF-BF stereo pair and so on. This strategy is similar to the approach
applied to image sequences or the three-camera setup with short and long base lengths. The success rate for the case shown in Table 5.6 improved with the view-by-view matching to 44'753 of 47'010 points for BF (= 95.1%), 40'504 of 43'117 points for CF (= 93.9%) and 35'278 of 38'183 points for DF (= 92.4%). So, 35'278 points could be matched in this way from AN to DF as opposed to only 27'941 points with the direct method. Of course, this view-by-view matching is only successful for cloud features that are still self-similar after 3.5 minutes (= time delay between DF and AN). For turbulent cloud structures other matching methods similar to the ones mentioned in the section on ground-based tracking (Section 4.1.4) should be considered.

Table 5.6: Success rate (= # matched points / # points) of the MPGC LSM algorithm with different camera combinations on the original level.

<table>
<thead>
<tr>
<th></th>
<th>AN-AA</th>
<th>AN-AF</th>
<th>AN-BF</th>
<th>AN-CF</th>
<th>AN-DF</th>
</tr>
</thead>
<tbody>
<tr>
<td># points</td>
<td>52877</td>
<td>52214</td>
<td>48512</td>
<td>42653</td>
<td>35730</td>
</tr>
<tr>
<td># matched points</td>
<td>49840</td>
<td>49329</td>
<td>42751</td>
<td>35241</td>
<td>27941</td>
</tr>
<tr>
<td>Success rate [%]</td>
<td>94.3</td>
<td>94.5</td>
<td>88.1</td>
<td>82.6</td>
<td>78.2</td>
</tr>
<tr>
<td>Iterations/point</td>
<td>5.7</td>
<td>5.7</td>
<td>7.8</td>
<td>9.1</td>
<td>9.8</td>
</tr>
</tbody>
</table>

The Meteosat-6 5-minute Rapid Scans during MAP, together with the images from the operational Meteosat-7 satellite, provided the possibility of stereo-viewing clouds over Europe with geostationary satellites for the first time (Seiz and Baltsavias, 2000b). As the Meteosat satellites have a reversed scan mode (south-north) with respect to all other meteorological satellites, their images cannot be used for stereo mapping with other geostationary satellites. The first stereo configuration with two Meteosat satellites outside of Europe was achieved with Meteosat-5 and Meteosat-7 over the Indian Ocean, when the Meteosat-5 satellite was placed at 63° E for the INDOEX project (Campbell and Holmlund, 2000). Unfortunately, the stereo configuration of Meteosat-6 and Meteosat-7 over Europe cannot be used for quantitative stereo analysis for three reasons. First, due to the small longitude difference of the two satellites, i.e. 0° and 9° W, compared to the satellite height, the base-to-height ratio is unfavorably low (≈ 0.16). Second, the two satellites are not synchronized, so that it is difficult to reach subpixel accuracy with matching, including for the necessary motion correction. For the Meteosat-6 5-minute Rapid Scans during MAP, the time difference was about 1 minute, while for the new Meteosat-6 10-minute configuration, the time difference is more than 5 minutes. And third, given the spatial resolution of 2.5 km x 4 km over Switzerland, small matching inaccuracies lead to rather large CTH errors, which are further enhanced with the low base-to-height ratio.

5.2.4 Geostationary stereo analysis

The Meteosat-6 5-minute Rapid Scans during MAP, together with the images from the operational Meteosat-7 satellite, provided the possibility of stereo-viewing clouds over Europe with geostationary satellites for the first time (Seiz and Baltsavias, 2000b). As the Meteosat satellites have a reversed scan mode (south-north) with respect to all other meteorological satellites, their images cannot be used for stereo mapping with other geostationary satellites. The first stereo configuration with two Meteosat satellites outside of Europe was achieved with Meteosat-5 and Meteosat-7 over the Indian Ocean, when the Meteosat-5 satellite was placed at 63° E for the INDOEX project (Campbell and Holmlund, 2000). Unfortunately, the stereo configuration of Meteosat-6 and Meteosat-7 over Europe cannot be used for quantitative stereo analysis for three reasons. First, due to the small longitude difference of the two satellites, i.e. 0° and 9° W, compared to the satellite height, the base-to-height ratio is unfavorably low (≈ 0.16). Second, the two satellites are not synchronized, so that it is difficult to reach subpixel accuracy with matching, including for the necessary motion correction. For the Meteosat-6 5-minute Rapid Scans during MAP, the time difference was about 1 minute, while for the new Meteosat-6 10-minute configuration, the time difference is more than 5 minutes. And third, given the spatial resolution of 2.5 km x 4 km over Switzerland, small matching inaccuracies lead to rather large CTH errors, which are further enhanced with the low base-to-height ratio.
Within Cloudmap2 there is a strong emphasis on the validation of macroscopic (Seiz et al., 2002) and microscopic (Schueller et al., 2002) cloud properties. The strategies for validation of satellite-derived cloud parameters from ATSR2 (AATSR), MISR, MODIS and, in a few months, SEVIRI include different approaches with increasing rigor. First, parameters that are derived from different satellite sensors or with different techniques from the same sensor can be compared. Second, validation with independent in situ radiosonde and aircraft data and ground-based stereo camera system and cloud radar data is performed. Finally, the results are compared with cloud information from operational NWP models for a better understanding of cloud representation in these models. Data assimilation tests with satellite- and ground-based cloud products will be done with the high-resolution MeteoSwiss aLMo model (De Morsier, 2002) in an attempt to improve initialization of the cloud water fields in the model.

In this thesis some results from all three validation categories are shown. First, a comparison of our stereo results from ATSR2 and MISR with other satellite-based cloud products is performed. Here, we concentrate on comparison of our results with operationally derived products, namely the RAL pre-operational near-realtime cloud-top pressure (CTP) product (Section 5.3.1.1) derived from ATSR2 data, which will be the main EUMETSAT CTP algorithm for SEVIRI, and the MISR L2TC stereo CTH and CTW products (Section 5.3.1.2). Then, results from comparisons with cloud radar products from Chilbolton and sounding data from Payerne, ETH, and Larkhill, UK, are shown. In Chapter 6, further validation of the satellite-based results using data from the ground-based imager system is presented and a short overview of the planned NWP experiments is given.
5.3.1 Other satellite-based CTH/CTW products

5.3.1.1 EUMETSAT/RAL CTP from ATSR2

The Rutherford Appleton Laboratory (RAL) enhanced cloud products (ECP) software currently produces near-realtime cloud products over specific Cloudmap2 target areas (e.g. Chilbolton) (RAL, 2002). The algorithms were developed in cooperation with EUMETSAT with the intent to use them for the new SEVIRI instrument on board MSG, which has similar spectral channels to ATSR2. The software computes both macroscopic (e.g. CTP) and microscopic (e.g. effective radius, optical depth, etc.) cloud parameters; the details for each parameter can be found in Watts et al. (1998). Cloud properties are retrieved using an optimal estimation method based on an explicit radiative transfer model. Values of variables required for the radiative transfer that are not well determined by the measurements (e.g. atmospheric temperature and humidity) are supplied from other sources (e.g. ECMWF model fields). Information on cloud-top pressure comes predominantly from the 11 $\mu$m and 12 $\mu$m channels. At these wavelengths there is no solar reflection, only emission by the cloud, atmosphere and surface. If the cloud is optically thick, the emitted radiation is nearly that of a black body at the cloud-top temperature. With corrections for absorption and emission by the atmosphere above the cloud, the cloud temperature can then be estimated. The atmospheric correction and the conversion to cloud-top pressure is accomplished with auxiliary data of atmospheric temperature and humidity from the ECMWF analysis fields. When the cloud is optically thin, there is significant transmission of radiation from the surface and atmosphere below the cloud and the observed radiance no longer represents the cloud-top temperature. However, simultaneous estimation of optical depth using the 0.87 $\mu$m channel and some of the retrieved microphysical parameters (e.g. particle size) allows the estimation scheme to correctly account for the transmission and fit the measured 11 $\mu$m and 12 $\mu$m radiances to an appropriate cloud-top pressure. The accuracy of the retrieved CTP values is 30 hPa which corresponds to a mean CTH error of 0.4 km.

5.3.1.2 Operational MISR L2TC CTH and CTW product

Stereo CTH on a 1.1 km x 1.1 km grid and CTW on a 70.4 km x 70.4 km grid are provided within the operational MISR processing chain as part of the L2TC cloud product. The algorithms for CTH and CTW retrieval are described in Diner et al. (1999b), Horvath and Davies (2001) and Moroney et al. (2002). The CTH and CTW for the high-resolution 1.1 km x 1.1 km CTH product are not retrieved simultaneously, but in two steps. First, camera triplets AN-BF-DF and/or AN-BA-DA are used to determine two CTW values for each 70.4 km x 70.4 km region with a histogram analysis. Second, matching results from the AN-AF and/or AN-AA camera pairs are converted into CTH and corrected for cloud motion over the 45 s between the acquisition of the two views. So, the principle of the MISR algorithm is similar to our combined ATSR2-Meteosat-6 approach of two-view matching with subsequent motion correction, except that only one instrument has to
be used in the MISR retrieval. The disadvantage in our approach of using two different satellites is that the cloud objects can be slightly different in shape, so that the height correction is not applied correctly, for example, at cloud borders. Furthermore, differences in the wavelengths of the channels that we used can lead to errors in the correction, especially for multi-layer cloud situations.

The disadvantage of the operational MISR L2TC approach is that large discontinuities in the sparse CTW field can have a significant effect on the quality of the L2TC StereoHeight product, even if the AN-AF and/or AN-AA image matching in the retrieval is accurate and reliable. The MISR L2TC StereoHeight product can thereby suffer from blockiness within the results (Figure 5.22, especially in the lower part of the map) that is introduced by large discontinuities in the sparse CTW field. Note that the disparities in the along-track disparity map of Figure 5.22 are continuous and the blocking is not present, which proves that the blocking is introduced in the second step of wind correction. The 70.4 km x 70.4 km CTW grid is probably too sparse, especially over land and mountainous terrain. It is likely that the wind field is not homogeneous within such a large grid cell and, as a consequence, the CTH field is not accurately corrected. In Horvath et al. (2002) first results with a denser CTW grid of 35.2 km x 35.2 km are presented and show potential improvements with the higher spatial resolution. Another important factor for the quality of the CTW field and, consequently, the CTH field is the matching method. Operationally, the so-called nested maximum (NM) matcher (Diner et al. 1999b; Muller et al. 2002) is used for getting the triplets in the first step; only in the second step, the more reliable M23 matcher is applied. Some matching tests on the 03/08/2000 dataset have shown that using the M23 matcher for both steps can improve significantly the CTW results and the blocking problem (Akos Horvath, personal communication).
For studying the vertical distribution of clouds, radars operating at millimeter wavelengths have proven to be an invaluable tool as they are sensitive to small particles and can penetrate multi-layered cloud systems. So, theoretically, cloud radars can provide validation data for both our cloud-base and cloud-top retrievals from stereo measurements. However, accurate retrieval of cloud boundaries from radar reflectivities is not always obvious. For example, cloud-base heights as measured by a cloud radar and a ceilometer can show significant differences that are caused by precipitating particles falling out of the cloud and giving a lower base height in the radar signal. Moreover, radar-derived cloud-top heights are underestimated in some cases either due to signal attenuation by liquid water or the lack of sufficient sensitivity to small cloud particles at cloud top.

The Chilbolton 94-GHz Galileo radar is located at (51.14 N, 1.44 W). The instrument is a bistatic system that operates continuously in a vertically-pointing configuration (Figure 5.23). The range resolution of the radar is 60 m. The Chilbolton radar used to be the only operational cloud radar in Europe. With the various measurement campaigns related to clouds within the two EU projects CLIWANET (2002) and Cloudnet (2002) cloud radar data are also available from a few other locations for specific time periods, e.g. Geesthacht, Paris and Cabauw. Unfortunately, neither Paris nor Cabauw are within the prolongation of the satellite paths over Switzerland. Geesthacht is within the ATSR2 and MISR paths over Switzerland, but no suitable data were available for the selected dates and overflight times. Therefore, only two cases over Chilbolton were analyzed.

Meteorological radar data are usually quantified as “radar reflectivity factor” $Z$. For liquid water drops in the Rayleigh scattering regime, the radar reflectivity is calculated as

$$Z = \int_0^\infty D^6 n(D) dD, \tag{5.10}$$

where $D$ is the diameter of the droplets and $n(D)dD$ is the droplet concentration within a given diameter bin of $D+dD$. So, with no differences in the scattering regime or in the dielectric constant
of the drops, the radar reflectivity is only dependent on the size of the drops and on their concentration. As soon as large-drop scattering and/or ice particles with a lower dielectric constant are involved, Equation 5.10 has to be adjusted to get the so-called effective reflectivity factor, as described in Hogan (1998). Examples of how to interpret cloud radar images are provided by Hogan (2002). At the ARM sites, as well as at the above mentioned European cloud radar locations, many research studies are ongoing to optimize cloud boundary retrieval from cloud radars (Danne et al., 1999; Clothiaux et al., 2000; Donovan et al., 2001). Within Cloudmap2 a new value-added procedure (VAP) for processing cloud radar data has been implemented (Clothiaux et al., 2002). All radar plots shown in this thesis were produced with this new cloud boundary detection software.

5.3.3 Radiosondes

Radiosonde measurements were described in detail in Section 4.2.2. For cloud-top estimation there is the additional difficulty that the time lag of hygristors and thermistors is much longer at colder temperatures. So, the estimated accuracy of CTH values from operational high-cost sonde profiles is about 200-300 m, depending of course on cloud type and height (Pierre Jeannet, personal communication). When using radiosondes, the maximum detectable cloud-top height is around 8-9 km, as at these heights the humidity in the atmosphere is already low and the variations difficult to measure at these low temperatures. The location of the tropopause according to the WMO definition can provide some information on the top heights of potential high cirrus layers which often follow this troposphere-stratosphere boundary (TPUB, 2002). The present WMO definition states that the “first tropopause” is defined as the lowest height at which the lapse rate decreases to 2°C per km or less, provided also that the average lapse rate between this height and all higher altitudes within 2 km does not exceed 2°C per km.

5.4 Comparison and validation results

For comparison and validation of our cloud height retrievals, six “golden” data sets were chosen within the time period from 1999 to 2002 that have coincident measurements from different satellite platforms as well as in situ and ground-based sensors. Three cases are without coincident skycam measurements (28/06/2000, 03/08/2000, 13/06/2001), while three cases are with coincident skycam results (13/10/1999, 12/04/2002, 19/04/2002). The 13/10/1999 (ATSR2) and the 19/04/2002 (MISR) cases contain only one satellite data set and are therefore presented in Chapter 6 in combination with the skycam measurements. In Table 5.7 all comparison cases that we now discuss are summarized.
5.4.1 Case 1: ATSR2-MISR-Meteosat-7-Radar-Radiosonde

For this case coincident cloud-top retrievals from ATSR2, MISR and Meteosat-7 are compared, together with cloud profile data from the Chilbolton radar and the Larkhill sounding. The five MISR views DF through AN, which are most coincident in time with the ATSR2 views, are analyzed for this case. The exact acquisition times of each sensor and each viewing angle are given in Table 5.8. From the ATSR2 false color image (Figure 5.24) and the radar time series plot (Figure 5.25) the cloud situation can be classified as one-layer stratus.

The ATSR2 results are summarized in Table 5.9. From CTH1 (i.e. with no geolocation and motion corrections) to CTH2 the y-disparity correction of -3.2 pixel, as described in Section 5.1.1, was applied. From CTH2 to the final CTH3 the preliminary stereo height (CTH2) was corrected by the cloud motion related height error. The height correction amount $h_{corr}$ was derived from the cloud-top wind components $(u, v)$, retrieved from a set of tracked cloud points in the Meteosat-7 (M7) VIS images. The CTW values were resampled onto the along-/cross-track grid of ATSR2 $(u', v')$ and MISR $(u'', v'')$, which are rotated against the geographical lat/lon grid by 14° CW for ATSR2 and 12° CW for MISR.

The MISR results (Table 5.10) are calculated from matched pairs and triplets of cloud points in the MISR L1B2 images. The BF view was used as the template and the other four views as patches. The results from the three different triplets show that the “widest” triplet combination (AN_BF_DF) yields the lowest height variability, which can be explained mathematically by the larger determinant in the linear equation system. The along-track motion component $v''$ is higher than the corresponding Meteosat-7 value, which results in slightly higher CTH3 values of the triplet results. The large standard deviation in the along-track wind component shows the difficulty

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>ATSR2</th>
<th>MISR</th>
<th>ASTER</th>
<th>Met-6/-7</th>
<th>Radar</th>
<th>Radiosonde</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28-06-2000</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>7</td>
<td>x</td>
<td>Larkhill</td>
</tr>
<tr>
<td>2</td>
<td>03-08-2000</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>6, 7</td>
<td>-</td>
<td>Payerne</td>
</tr>
<tr>
<td>3</td>
<td>13-06-2001</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>6, 7</td>
<td>x</td>
<td>Larkhill</td>
</tr>
<tr>
<td>4</td>
<td>12-04-2002</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>6</td>
<td>-</td>
<td>ETH</td>
</tr>
</tbody>
</table>

Table 5.7: Overview of satellite-based comparison cases.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Acquisition time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR2</td>
<td>Forward view: 11:15:11.9 - 11:16:27.8, nadir view: 11:17:26.4 - 11:18:42.3</td>
</tr>
<tr>
<td>Meteosat-7</td>
<td>10:53 / 11:23 / 11:53</td>
</tr>
</tbody>
</table>

Table 5.8: Exact acquisition times (UTC) of ATSR2, MISR and Meteosat-7 images for the 28/06/2000 case.
of separating along-track parallax due to height from along-track parallax due to cloud motion, even with our MPGC LSM method with sub-pixel accuracy. At any rate, simultaneous CTH/CTW retrieval from MISR is possible, at least for this one layer cloud situation, with standard deviations of $\pm 2$ m/s for the EW motion component, $\pm 3$ m/s for the NS motion component and $\pm 400$ m (height error + motion error) for CTH.

The operational NASA JPL L2TC product reports a cloud-top height of $2.3 \pm 0.1$ km, an along-track ("NS") cloud velocity of -0.8 m/s and an across-track velocity of 0.2 m/s over Chilbolton. So, the CTH is underestimated in the L2TC product by about 200-300 m due to the along-track CTW, which is too low compared to our Meteosat-7 and MISR L1B2 CTW results. Nonetheless, the L2TC results are reasonable for this case as there are not many blunders that are readily apparent and blockiness from the 70.4 km x 70.4 km CTW retrieval is less obvious. Overall, we conclude that the triplet matching approach works well for a single layer cloud situation.

Inspecting the radar reflectivity at 11:20 UTC (Figure 5.25), a cloud-top height of 2.4 km AGL is found, which is 2.5 km ASL. This cloud-top height corresponds well to the combined MISR-Meteosat-7 results, especially from the inner three views (AN, AF, BF), while the L1B2 triplet results are 100-200 m too high.

<table>
<thead>
<tr>
<th>ATSR2</th>
<th>CTH1 [km]</th>
<th>CTH2 [km]</th>
<th>$u'$ [m/s] (x_dis)</th>
<th>$u'$ [m/s] (M7)</th>
<th>$v'$ [m/s] (M7)</th>
<th>h_corr [km]</th>
<th>CTH3 [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>v870</td>
<td>4.3 $\pm$ 0.2</td>
<td>2.0 $\pm$ 0.2</td>
<td>5.5</td>
<td>-0.4</td>
<td>-3.4</td>
<td>+ 0.3</td>
<td>2.3 $\pm$ 0.2</td>
</tr>
<tr>
<td>ir11</td>
<td>4.6 $\pm$ 0.3</td>
<td>2.3 $\pm$ 0.3</td>
<td>-2.9</td>
<td>-0.4</td>
<td>-3.4</td>
<td>+ 0.3</td>
<td>2.6 $\pm$ 0.3</td>
</tr>
</tbody>
</table>

Table 5.9: ATSR2 CTH results for the 28/06/2000 case.
Figure 5.25: Chilbolton radar reflectivity (top) and cloud boundaries (bottom) plots for 28/06/2000.
In this case coincident cloud-top measurements from ATSR2, MISR and Meteosat-6 10-minute Rapid Scans are compared, together with cloud profile data from the Payerne sounding. This constellation of measurements was the only coincidence of ATSR2, Meteosat-6 and MISR over Switzerland in 2000. The exact acquisition times of the three satellite sensors are given in Table 5.11.

In the cloud-top height maps from MISR (Figure 5.28) two cloud systems can be distinguished, one at heights of 6000 m and higher and a second one with many smaller cloud objects towards the west at lower heights between 2000 m and 6000 m. The cloud systems can also be distinguished in the motion field extracted from the Meteosat-6 Rapid Scans (Figure 5.26), where the lower layers move much slower and more towards the east in contrast to the fast north-east moving high cloud layer. The wind correction for the ATSR2 cloud-top heights, as derived from the Meteosat-6 wind field, is summarized in Table 5.12. The along-track wind component is quite substantial in this case and leads to an overestimation of the ATSR2 stereo CTHs of up to 4.2 km for the cloud system over western Switzerland.

As we have pointed out in the theoretical part of this chapter, accurate estimation of the CTW field is probably the limiting factor of satellite-based stereo CTH accuracies, given the progress of the photogrammetric matching methods. Therefore, the along- and cross-track cloud motion components were analyzed in detail for this case. The effect of a denser CTW field is illustrated in Figure 5.26. Both motion fields were derived from Meteosat-6 10-minute Rapid Scans. The motion field on the left is from the 70.4 km x 70.4 km averaged vectors, similar to the resolution of the L2TC product, while the motion field on the right is on a denser grid of 35.2 km x 35.2 km. Comparing the motion fields with the underlying MISR image, the denser grid represents a much more realistic view of the actual cloud movements, so an extension of the MISR L2TC product to this resolution will be an important step towards an improved CTW field.

<table>
<thead>
<tr>
<th>MISR</th>
<th>CTH1 [km]</th>
<th>u'' [m/s]</th>
<th>v'' [m/s]</th>
<th>hcorr</th>
<th>CTH3 [km]</th>
<th>v'' [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF_DF</td>
<td>2.4 ± 0.1</td>
<td>-0.7 ± 1.6</td>
<td>-3.4</td>
<td>+ 0.190</td>
<td>2.6 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>BF_CF</td>
<td>2.3 ± 0.1</td>
<td>-1.0 ± 1.6</td>
<td>-3.4</td>
<td>+ 0.260</td>
<td>2.6 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>AF_BF</td>
<td>2.2 ± 0.1</td>
<td>-0.8 ± 1.7</td>
<td>-3.4</td>
<td>+ 0.300</td>
<td>2.5 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>AN_AF</td>
<td>2.1 ± 0.2</td>
<td>-0.6 ± 1.6</td>
<td>-3.4</td>
<td>+ 0.320</td>
<td>2.4 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>BF_CF_DF</td>
<td>-</td>
<td>-1.0 ± 1.6</td>
<td>-</td>
<td>-</td>
<td>2.6 ± 0.2</td>
<td>-4.9 ± 2.7</td>
</tr>
<tr>
<td>AN_BF_DF</td>
<td>-</td>
<td>-0.9 ± 1.6</td>
<td>-</td>
<td>-</td>
<td>2.6 ± 0.1</td>
<td>-5.6 ± 1.8</td>
</tr>
<tr>
<td>AN_BF_CF</td>
<td>-</td>
<td>-0.8 ± 1.6</td>
<td>-</td>
<td>-</td>
<td>2.7 ± 0.2</td>
<td>-6.1 ± 2.7</td>
</tr>
</tbody>
</table>

Table 5.10: MISR L1B2 CTH/CTW results for the 28/06/2000 case.

5.4.2 Case 2: ATSR2-MISR-Meteosat-6-Meteosat-7-Radiosonde

In this case coincident cloud-top measurements from ATSR2, MISR and Meteosat-6 10-minute Rapid Scans are compared, together with cloud profile data from the Payerne sounding. This constellation of measurements was the only coincidence of ATSR2, Meteosat-6 and MISR over Switzerland in 2000. The exact acquisition times of the three satellite sensors are given in Table 5.11. In the cloud-top height maps from MISR (Figure 5.28) two cloud systems can be distinguished, one at heights of 6000 m and higher and a second one with many smaller cloud objects towards the west at lower heights between 2000 m and 6000 m. The cloud systems can also be distinguished in the motion field extracted from the Meteosat-6 Rapid Scans (Figure 5.26), where the lower layers move much slower and more towards the east in contrast to the fast north-east moving high cloud layer. The wind correction for the ATSR2 cloud-top heights, as derived from the Meteosat-6 wind field, is summarized in Table 5.12. The along-track wind component is quite substantial in this case and leads to an overestimation of the ATSR2 stereo CTHs of up to 4.2 km for the cloud system over western Switzerland.

As we have pointed out in the theoretical part of this chapter, accurate estimation of the CTW field is probably the limiting factor of satellite-based stereo CTH accuracies, given the progress of the photogrammetric matching methods. Therefore, the along- and cross-track cloud motion components were analyzed in detail for this case. The effect of a denser CTW field is illustrated in Figure 5.26. Both motion fields were derived from Meteosat-6 10-minute Rapid Scans. The motion field on the left is from the 70.4 km x 70.4 km averaged vectors, similar to the resolution of the L2TC product, while the motion field on the right is on a denser grid of 35.2 km x 35.2 km. Comparing the motion fields with the underlying MISR image, the denser grid represents a much more realistic view of the actual cloud movements, so an extension of the MISR L2TC product to this resolution will be an important step towards an improved CTW field.
Our matching results with a compact triplet (AN-AF-BF) are shown in Figure 5.28. The single triplet results are quite noisy due to the low separability of the cloud height and along-track motion for this triplet combination. By applying a strict quality control on outliers and averaging the results over a 17.6 km x 17.6 km grid, smooth CTH and CTW fields were obtained. Comparisons of the CTW fields extracted with different matching methods are illustrated in Figure 5.27. From the MPGC LSM matching we obtain a smooth CTW field from the AN-AF-CF triplet (Figure 5.28), while there are larger deviations in the M23 and NM matching results. The NM cloud motion field, in particular, shows many blunders. Due to the non-subpixel accuracy of the NM and M23 matchers, their single triplet wind values would be much noisier than the winds obtained from our MPGC LSM algorithm. To compensate, the NM values are sorted into a histogram and the two peak values within the histogram are taken as the cloud motion winds. Depending on the density of the matched points, different resolutions of the final CTW grid are appropriate. For the operational 70.4 km x 70.4 km grid the number of points from the NM matcher are normally sufficient, while for the tests on a 35.2 km x 35.2 km grid the M23 matcher was used to ensure a sufficient number of points (Horvath et al., 2002).

As validation, the satellite-based results were extracted and compared at the location of the Aerological station of MeteoSwiss at Payerne (Table 5.13). Data from the sounding launched at Payerne at 12:00 UTC on this day are displayed in Figure A.4. At least five potential cloud layers can be identified in the sounding, with two of them being thin layers around 9 km and 10 km above sea level, so hardly detectable by the currently operational sounding sensors (Section 4.2.2), and

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Acquisition time over Payerne (46.82 N / 6.95 E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR2</td>
<td>Forward view: 10:45:40, nadir view: 10:47:28</td>
</tr>
<tr>
<td>MISR</td>
<td>DF: 10:50:47, ..., AN: 10:54:13</td>
</tr>
<tr>
<td>Meteosat-6</td>
<td>10:37, 10:47, 10:57</td>
</tr>
</tbody>
</table>

Table 5.11: Exact acquisition times (UTC) of ATSR2, MISR and Meteosat-6 data on 03/08/2000.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>x wind component [m/s]</td>
<td>12.3 ± 5.1</td>
<td>1.6</td>
<td>34.3</td>
</tr>
<tr>
<td>y wind component [m/s]</td>
<td>12.5 ± 10.0</td>
<td>-17.3</td>
<td>42.6</td>
</tr>
<tr>
<td>x-shift [m]</td>
<td>1518.0 ± 628.5</td>
<td>183.5</td>
<td>3830.4</td>
</tr>
<tr>
<td>y-shift [m]</td>
<td>1538.9 ± 1219.2</td>
<td>-1818.5</td>
<td>4643.4</td>
</tr>
<tr>
<td>Height correction [m]</td>
<td>-1229.2 ± 962.5</td>
<td>-4179.1</td>
<td>1673.0</td>
</tr>
</tbody>
</table>

Table 5.12: Statistics of the ATSR2 wind correction on 03/08/2000. The x-axis is positive towards the east and the y-axis positive towards the north, so westerly and southerly winds are positive while easterly and northerly winds are negative. The height correction is positive for northerly winds (underestimation of the stereo CTHs) and negative for southerly winds (overestimation of the stereo CTHs).
Figure 5.26: Meteosat-6 CTW vectors over MISR AN image on 03/08/2000 (wind barbs in knots, 1 kn $\approx$ 2 m/s). Left: 70.4 km x 70.4 km resolution; right: 35.2 km x 35.2 km resolution.

Figure 5.27: Comparison of cloud motion fields for different matching algorithms on 03/08/2000. Left: MISR L2TC CTW derived with NM matcher (wind barbs in m/s); right: L2TC CTW derived with M23 matcher (wind barbs in m/s). The MPGC LSM matcher results are shown in Figure 5.28.
Figure 5.28: MISR L1B2 CTH and CTW results retrieved from the AN-AF-BF triplet and averaged on a 17.6 km x 17.6 km grid. Top left: cross-track motion component [m/s]; top right: along-track motion component [m/s]; bottom left: cloud-top height [m ASL]; bottom right: CTH and CTW extracted from the MISR L1B2 triplet AN-AF-CF (wind barbs in knots).

<table>
<thead>
<tr>
<th>Payerne, 46.82 N, 6.95 E</th>
<th>CTH2</th>
<th>( u'/u'' )</th>
<th>( v'/v'' )</th>
<th>( h_{corr} )</th>
<th>CTH3</th>
<th>( u'/u'' )</th>
<th>( v'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR2, 0.67 ( \mu m )</td>
<td>11013.9</td>
<td>21.2</td>
<td>33.6</td>
<td>-3235.4</td>
<td>7778.5</td>
<td>16.1</td>
<td>-</td>
</tr>
<tr>
<td>ATSR2, 11.0 ( \mu m )</td>
<td>12227.2</td>
<td>21.2</td>
<td>33.6</td>
<td>-3235.4</td>
<td>8991.8</td>
<td>22.0</td>
<td>-</td>
</tr>
<tr>
<td>MISR AN-AF</td>
<td>11034.6</td>
<td>22.8</td>
<td>33.7</td>
<td>-3315.1</td>
<td>7719.5</td>
<td>25.1</td>
<td>-</td>
</tr>
<tr>
<td>MISR AN-BF</td>
<td>10821.3</td>
<td>22.8</td>
<td>33.7</td>
<td>-3114.9</td>
<td>7706.5</td>
<td>25.6</td>
<td>-</td>
</tr>
<tr>
<td>MISR AN-AF-BF</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7506.8</td>
<td>25.4</td>
<td>36.2</td>
</tr>
</tbody>
</table>

Table 5.13: Comparison of CTH and CTW results of ATSR2+Meteosat-6, MISR+Meteosat-6 and MISR-three views at Payerne, Switzerland, on 03/08/2000. All winds are given in the satellite reference grids.
three of them being thicker layers 7.5 km, 3.8 km and 2.0 km above sea level. The ATSR2 results from the visible and IR channels show again that thin cirrus clouds are normally only detected with stereo matching in the IR channel. Note that the CTW EW ($u'$) values, extracted from only the MISR cross-track disparities, are in good agreement with the Meteosat-6 CTW EW values.

### 5.4.3 Case 3: ATSR2-MISR-Meteosat-6-Meteosat-7-Radar-Radiosonde

On 13/06/2001, coincident cloud-top measurements from ATSR2, MISR, Meteosat-6 10-minute Rapid Scans and Meteosat-7 are compared, together with cloud profile data from the Chilbolton radar and the Larkhill sounding. The exact acquisition times of the data are listed in Table 5.14. From the video camera image (Figure 5.29) and the radar reflectivity plot (Figure 5.30) a broken cloud situation with multiple, mainly two, cloud layers can be identified.

The ATSR2 CTH results are summarized in Table 5.15. From CTH1 to CTH2 the retrieved y-disparity was corrected by the y-shift, calculated from matched points along the Southern coastline of England. The following x- and y-shifts (ATSR2 relative geolocation errors between nadir and forward channels) were applied: $dx = +105.0$ pixels and $dy = +2.8$ pixels. From CTH2 to the final CTH3 the preliminary stereo height (CTH2) was corrected by the cloud motion related height error. The height correction amount $h_{corr}$ was derived from the cloud motion wind components ($u$, $v$), calculated from a set of tracked cloud points in the Meteosat-6 (M6) and Meteosat-7 VIS images. The CTW values ($u$, $v$) are resampled to the along-/cross-track grid of ATSR2 ($u'$, $v'$) and MISR ($u''$, $v''$), which are rotated against the geographical lat/lon grid by 14° CW for ATSR2 and 12° CW for MISR.

For this case all MISR views, except the missing DF image, were analyzed (Table 5.16) as we expected to find height differences between camera pair results, given the broken cloud situation and the 6-minute difference between DA and CF camera images. As there are no geolocation shifts between the MISR L1B2 views, CTH1 is equal to CTH2. For pairs of points CTH3 is derived in the same way as for ATSR2, by correcting the preliminary height CTH1 by the motion error calculated from Meteosat VIS data. For triplets of points CTH3 and $v''$ can be calculated directly without the use of external motion information. We find that the triplet results are much

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Acquisition time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR2</td>
<td>Forward view: 11:15:11.6 - 11:16:27.5, nadir view: 11:17:26.41 - 11:18:42.0</td>
</tr>
<tr>
<td>Meteosat-6</td>
<td>11:07/ 11:17/ 11:27</td>
</tr>
<tr>
<td>Meteosat-7</td>
<td>10:53/ 11:23/ 11:53</td>
</tr>
</tbody>
</table>

Table 5.14: Exact acquisition times (UTC) of ATSR2, MISR, Meteosat-6 and Meteosat-7 data on 13/06/2001.
Figure 5.29: Left: cloud situation over Chilbolton on 13/06/2001 at 11:15 UTC; right: ATSR2 CTP results from RAL.

<table>
<thead>
<tr>
<th>ATSR2</th>
<th>CTH1 [km]</th>
<th>CTH2 [km]</th>
<th>( u' ) [m/s]</th>
<th>( u'' ) [m/s]</th>
<th>( v'' ) [m/s]</th>
<th>( h_{\text{corr}} ) [km]</th>
<th>CTH3 [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>v870</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ir11</td>
<td>2.8 ± 0.3</td>
<td>4.8 ± 0.3</td>
<td>8.4</td>
<td>4.6</td>
<td>3.2</td>
<td>-0.3</td>
<td>4.5 ± 0.3</td>
</tr>
</tbody>
</table>

Table 5.15: ATSR2 CTH results on 13/06/2001. Due to the smaller swath width of the v870 channel and the x-shift of over 100 pixels, Chilbolton is only visible in the nadir view of the v870 channel (no stereo).

<table>
<thead>
<tr>
<th>MISR</th>
<th>CTH1 [km]</th>
<th>( u'' ) [m/s]</th>
<th>( u'' ) [m/s]</th>
<th>( v'' ) [m/s]</th>
<th>( h_{\text{corr}} ) [km]</th>
<th>CTH3 [km]</th>
<th>( \psi' ) [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF_CF</td>
<td>4.5 ± 0.2</td>
<td>7.0 ± 0.9</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.230</td>
<td>4.3 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>AF_BF</td>
<td>4.7 ± 0.2</td>
<td>6.1 ± 0.8</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.270</td>
<td>4.4 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>AN_AF</td>
<td>4.7 ± 0.1</td>
<td>6.4 ± 0.5</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.300</td>
<td>4.4 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>AA_AN</td>
<td>4.6 ± 0.2</td>
<td>5.4 ± 0.6</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.320</td>
<td>4.3 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>BA_AA</td>
<td>4.8 ± 0.2</td>
<td>7.3 ± 1.2</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.320</td>
<td>4.5 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>BA_AA_AN</td>
<td>-</td>
<td>6.4 ± 0.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.5 ± 0.9</td>
<td>1.7 ± 8.6</td>
</tr>
<tr>
<td>BA_AN</td>
<td>4.8 ± 0.3</td>
<td>6.3 ± 0.7</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.320</td>
<td>4.5 ± 0.3</td>
<td>-</td>
</tr>
<tr>
<td>DA_BA</td>
<td>4.7 ± 0.3</td>
<td>6.2 ± 1.0</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.320</td>
<td>4.5 ± 0.3</td>
<td>-</td>
</tr>
<tr>
<td>DA_AN</td>
<td>4.8 ± 0.2</td>
<td>6.2 ± 0.7</td>
<td>4.7</td>
<td>3.1</td>
<td>-0.320</td>
<td>4.5 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>DA_BA_AN</td>
<td>-</td>
<td>-0.8 ± 1.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.6 ± 0.5</td>
<td>2.8 ± 5.3</td>
</tr>
</tbody>
</table>

Table 5.16: MISR L1B2 CTH/CTW results on 13/06/2001.
Figure 5.30: Chilbolton radar reflectivity (top) and cloud boundaries (bottom) plots for 13/06/2001.
noisier than the M7 results for this case. The DA-BA-AN triplet results are better than the more compact BA-AA-AN triplet results due to the mathematically better separability. One reason for the noisy DA-BA-AN results could be that the cloud-top height is not constant over the 3.5-minute period between AN and DA camera image acquisitions which can be seen in the radar profiles. However, a significant CTH difference between the subsequent two-view combinations could not be detected.

The operational MISR L2TC product has the same problem of a high standard deviation in the cloud-top height results (Table 5.17). The CTW from the 70.4 km x 70.4 km histogram analysis is in good correspondence with the Meteosat-6 and Meteosat-7 CTW, which illustrates the advantage of the histogram analysis against averaging of the single triplet results. While the L2TC CTH results are noisy, they nonetheless have a mean and median CTH which corresponds nicely with the ATSR2, MISR L1B2 and Chilbolton radar CTH results. The ATSR2 CTP results from RAL (Figure 5.29) show a CTP at Chilbolton of about 600 hPa, which corresponds to a cloud-top height of about 4.2 km ASL.

<table>
<thead>
<tr>
<th>MISR L2TC</th>
<th>CTH [km]</th>
<th>CTW_EW [m/s]</th>
<th>CTW_NS [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.7 ± 1.1</td>
<td>5.1</td>
<td>3.1</td>
</tr>
<tr>
<td>(median: 4.4; min: 2.1; max: 7.7)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.17: MISR operational L2TC CTH/CTW results on 13/06/2001.

5.4.4 Case 4: MISR-ASTER-Meteosat-6-Skycam-Radiosonde

For the 12/04/2002 case, coincident cloud-top measurements from ASTER, MISR and Meteosat-6 10-minute Rapid Scans are compared, together with cloud-base stereo imager results and cloud profile data from the ETH and Payerne soundings. As described in Section 5.2, MISR AN-AF, or AN-AA, stereo CTH and ASTER stereo CTH have about the same motion errors, independent of the actual cloud height and cloud motion. This offers the possibility for high-resolution ASTER cloud matching that can be used as a validation digital surface model (DSM) for the coarser resolution MISR matching results. As shown in Figure 5.31, corresponding cloud features can be found between the MISR and ASTER images by taking the 4th pyramid level of ASTER and the original level of MISR. The cloud situation as seen by MISR and ASTER is presented in Figure 5.32.

The extracted height histograms from MISR L1B2 MPGC LSM matching, ASTER MPGC LSM matching and MISR L2TC M23 matching are shown in Figure 5.33. Overall, there is a good correspondence between all three extracted DSMs. The median difference between the MISR L1B2 and the ASTER heights is +248.3 m (MISR > ASTER), which is less than one pixel matching error at the MISR resolution. However, the ASTER histogram is broader, which is introduced either
by matching errors due to the higher resolution of the land areas that are visible between the clouds or by the difference of matching in the MISR red images against matching in the ASTER NIR channels. For the L2TC M23 matching results, the quantized cloud-top heights due to the pixel-only accuracy of the M23 matcher are readily apparent. The lower of the two large peaks corresponds with our MISR and ASTER results, but on average, the MISR L2TC results are higher than our MISR L1B2/ASTER results. This bias in the MISR L2TC results could be caused by the L2TC algorithm keeping the higher value from the two matching combinations AN-AF and AN-AA.

**5.4.5 Summary of satellite-based comparison cases**

A summary of the results of all comparison cases, including the theoretical accuracies of each measurement method, is presented in Table 5.18. The satellite results are based on a 10 km x 10 km box centered at Chilbolton (cases 1 and 3), Payerne (case 2) and Zürich-Kloten (case 4); the 10 s radar cloud-top height values are averaged over 5 min during the satellite overpass times. The theoretical accuracies of the stereo retrievals (ATSR2, MISR L1B2, ASTER and MISR L2TC) are calculated according to Table 5.5 and incorporate the stereo configuration (i.e. base-to-height ratio), the measurement accuracy and the accuracy of the wind correction. The parallax measurement accuracy of our MPGC LSM matcher is taken as 0.5 pixel and the MISR L2TC M23 matcher accuracy as 1.0 pixel; the accuracy of the external cloud motion retrieval from the Meteosat-6 Rapid Scans is about 3 m/s. According to Horvath and Davies (2001) and Moroney et al. (2002), the along-track motion retrieval accuracy of the MISR L2TC product is 3 m/s as well, although we consider this value to be rather optimistic. The total error $\sigma_{theor}$ is then calculated from the two components $\sigma_{CTH}$ and $\sigma_{CTW}$ as

\[
\sigma_{theor}^2 = \sigma_{CTH}^2 + \sigma_{CTW}^2.
\] (5.11)
Figure 5.32: MISR and ASTER images on 12/04/2002. Left: MISR AN NIR_R_G false color image; right: ASTER anaglyph image rotated by 90° CCW.

Figure 5.33: CTH histogram for the results from ASTER (MPGC LSM matcher), MISR L1B2 (MPGC LSM matcher) and MISR L2TC (M23 matcher). No cloud motion correction was applied to the data so the CTH values are not absolute.
The error estimates $\sigma_{theor}$ do not contain the influence of geolocation or orientation parameter inaccuracies or the uncertainties due to the obvious problems of cloud boundary definition. The influence of geolocation or orientation errors could be included by increasing the parallax uncertainty, while a realistic estimation of errors due to cloud boundary definition is not possible.

The accuracy of the ATSR2 RAL CTP retrieval is 30 hPa which corresponds to a mean CTH error of 0.4 km. The radar accuracy depends on cloud type and droplet/crystal distribution but it is certainly larger than the sample resolution of 60 m. With the carbon hygristor humidity measurements of the available soundings, the CTH retrieval accuracy of potential cloud layers is about 200-300 m (Pierre Jeannet, personal communication; Naud et al., 2003).
Chapter 6

Combination of ground- and satellite-derived cloud geometry

Clouds are a major contributor to our uncertainty of climate processes and climate change. The cloud products derived from satellite- and ground-based stereo systems characterize only limited aspects of the cloud fields. In this chapter these photogrammetrically-derived cloud-top and bottom boundaries (Figure 6.1) are compared and possibilities for combination and application in cloud and NWP models are outlined. The combined use of in situ, satellite- and ground-based sensors for the examination of cloud systems and structures has also been realized in a few recent investigations and measurement campaigns (Feijt and van Lammeren, 1996; Liou et al., 2002; ARM, 2002; CLIWANET, 2002; Cloudnet, 2002). The exploitation of these macro- and micro-physical cloud data sets will help to improve significantly the representation of clouds in operational NWP models.

6.1 Ground- and satellite-derived cloud geometry

Three coincident ground- and satellite-based measurements of clouds with stereo sensors were acquired in Switzerland from 1999 through 2002. The dates and satellite sensors are summarized in Table 6.1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>ATSR2</th>
<th>MISR</th>
<th>ASTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13-10-1999</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>12-04-2002</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>19-04-2002</td>
<td>-</td>
<td>x</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.1: Overview of coincident ground- and satellite-based stereo measurement cases.
6.1.1 Case 1: ATSR2-Skycam

A description of the synoptic situation on 13/10/1999 with forecast reports and a hindcast summary can be found at http://www.map.ethz.ch (IOP-06). The exact acquisition times of ATSR2, Meteosat-6 and the ground-based stereo imager data are listed in Table 6.2. The wind field, as derived from the Meteosat-6 rapid scans, shows strong westerly flow over the Alpine Region, including the “Rhine Valley” target area.

Our ground-based camera system was the validation instrument for cloud-base heights of vertically thin clouds (e.g. contrails) and for three-dimensional cloud motion of every visible cloud point within the overlap region of the ground-based cameras. The spatial extent of this overlap region depends on the camera lenses (i.e. rectilinear or fish-eye) and cloud height (Equation 2.1). For this case the two cameras were equipped with rectilinear 18 mm lenses with view angles of 100° and the mean cloud height was 10 km. Therefore, an area of approximately 15 km x 10 km can be used for the stereo-photogrammetric analysis (Figure 6.2).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Acquisition time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteosat-6</td>
<td>10:11 / 10:16 / 10:21</td>
</tr>
<tr>
<td>Skycam</td>
<td>10:14 / 10:16 / 10:18 / 10:20</td>
</tr>
</tbody>
</table>

Table 6.2: Exact acquisition times (UTC) of ATSR2, Meteosat-6 and ground-based camera system data on 13/10/1999.
Figure 6.2: ATSR2 11.0 μm channel image (left; zoom: top right) and corresponding ground-based camera image (bottom right) at Rhine Valley, Switzerland on 13/10/1999. The skyCam stereo FOV corresponds to the red rectangle within the ATSR2 image and contains approximately 14 x 9 ATSR2 pixels. The small-scale lower layer cloud structures in the center of the skyCam FOV are not visible in the ATSR2 image because of the higher layer at 11.0 km and/or due to the low spatial resolution of 1 km.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Cloud height [km]</th>
<th>Cloud wind [m/s]</th>
<th>Cloud wind direction [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR2</td>
<td>0.87 μm: 10.2 ± 0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>11.0 μm: 11.3 ± 0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Meteosat-6</td>
<td>-</td>
<td>19.3</td>
<td>275</td>
</tr>
<tr>
<td>Skycam</td>
<td>lower layer</td>
<td>8.0 ± 0.11</td>
<td>274</td>
</tr>
<tr>
<td></td>
<td>upper layer</td>
<td>10.9 ± 0.13</td>
<td>276</td>
</tr>
</tbody>
</table>

Table 6.3: Cloud parameters derived over Rhine Valley on 13/10/1999 from ATSR2, Meteosat-6 and the ground-based imager system. The ATSR2 results are for a box of 20 x 20 pixels (including the area shown as red rectangle in Figure 6.2), while the Meteosat-6 results are for a box of 8 x 5 pixels.
Figure 6.3: Ground-based enhanced image from “west” camera at 10:35:00 UTC on 12/04/2002 at the ASTER overflight time.

The extracted ATSR2 CTH and Meteosat-6 cloud motion within the camera field of views is shown in Table 6.3. The retrieved mean cloud-top height in this area is 11.3 km above sea-level from the ATSR2 11.0 μm channel and 10.2 km from the ATSR2 0.87 μm channel. Note that only the upper layer is detected by the 11.0 μm channel, while in the 0.87 μm channel cloud points in both the lower and higher layers are detected. In the ground-based images two layers of clouds are visible. This case amply demonstrates the validation of satellite-derived cloud-top heights of vertically thin clouds using ground-based imagers. Moreover, the ground-based stereo camera system provides additional smaller scale cloud features within the cameras' FOV which can be important for regional nowcasting.

6.1.2 Case 2: ASTER-MISR-SkyCam

For the 12/04/2002 case, the overlapping area of the ground-based images corresponds to 13.1 km in x-direction and 10.3 km in y-direction. For the analysis the image acquired at 10:35 UTC was used (Figure 6.3), as it was in exact coincidence with the MISR and ASTER nadir image acquisitions. The 60 km x 60 km FOV of ASTER over Zürich-Kloten is shown in Figure 6.4. Although the ETH sounding data (Figure A.7) contains various potential cloud layers, the stereo results obtained from the ground and satellite data exhibit detection of the same high cirrus clouds (Table 6.4). For the ASTER CTHs a mean motion correction of -429 m had to be applied due to an along-track motion component of about 4.4 m/s (south to north) on average. The comparison of the ASTER CTHs to MISR CTHs is shown in Section 5.4.4.
6.1.3 Case 3: MISR-Skycam

In this third ground-satellite combination case, there is a two-layer cloud system over the area of Zürich-Kloten: lower-level broken Sc clouds with a higher semi-transparent thin As, or Ci, layer. In the two anaglyph images in Figure 6.5 these cloud layers can be seen relative to each other in 3D. In Figure 6.6 the view point is turned around as we now look up from the camera system to the base of the cloud objects. Due to the small height of the Sc clouds (2.0-2.5 km ASL), the skycam image overlap area corresponds to only about 2.5 km x 1.7 km.

Motivated by the high thin cloud layer, two MISR matching camera pairs, i.e. AN-AF and CF-DF, were used in an attempt to detect and to vertically map the thin cloud layer in the more oblique CF-DF viewing angle combination. The MISR CTH results (Figure 6.7), however, show no significant difference between the two view combinations near Zürich-Kloten. The motion error is negligible for this case as the motion is mainly in the cross-track direction. The along-track motion component is only -0.9 m/s (north to south) which leads to a motion correction of only +88 m for the AN-AF constellation and +50 m for the CF-DF preliminary heights. The cloud-base heights extracted from the skycam stereo pair at 10:41 UTC have an average of 2.1 km ASL, a standard

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Preliminary CTH [m]</th>
<th>Final CTH / CBH [m]</th>
<th>Std. dev. [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTER</td>
<td>11'488.3</td>
<td>11'059.3</td>
<td>1'189.4</td>
</tr>
<tr>
<td>Skycam</td>
<td>-</td>
<td>10'868.4</td>
<td>968.2</td>
</tr>
</tbody>
</table>

Table 6.4: CTH and CBH results from ASTER and the ground-based camera system, respectively, on 12/04/2002. Preliminary CTH for ASTER is the CTH before the motion correction.
Figure 6.5: Anaglyph images from MISR on 19/04/2002. AN + BF views were combined; both images are rotated by 90° CCW. Left: larger scan area; right: zoom at the area of Zürich-Kloten.

Figure 6.6: Anaglyph image of the ground-based stereo pair at 10:35 UTC on 19/04/2002.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>CTH / CBH [m]</th>
<th>Std. dev. [m]</th>
<th>Accuracy $\sigma_{bear}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISR</td>
<td>3'500</td>
<td>364</td>
<td>300</td>
</tr>
<tr>
<td>Skycam</td>
<td>2'133</td>
<td>148</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 6.5: CTH and CBH results from MISR and the ground-based camera system, respectively, on 19/04/2002 at 10:41 UTC.
deviation of only 148 m and a range from 1860 m to 3061 m. Compared with the CTH values from MISR of about 2.9 - 3.9 km, the thickness of the Sc cloud layer is about 1'000 - 1'500 m. In the 10:41 UTC sky cam stereo pair, which is exactly coincident with the MISR AN acquisition, only the Sc is seen. As shown in Section 4.3, subsequent images (e.g. at 10:50 UTC) do image the higher cirrus layer through the holes in the lower cloud layer. The mean cloud-base height of this second layer, as extracted from the 10:50 UTC image, is $5.950 \pm 0.150$ km ASL.

### 6.2 Applications of combined cloud geometry

The stereoscopically-derived cloud products for April 2002 with coincident satellite and skycam measurements will be further exploited within Cloudmap2. In particular, these cloud products will
be used in radiative transfer simulations performed at the German Aerospace Center (DLR), as well as in planned assimilation tests with the operational NWP model of MeteoSwiss. We now briefly describe these two future studies in the following two paragraphs.

### 6.2.1 Application in cloud radiative transfer simulations

In the cloud radiative transfer study at the German Aerospace Center (DLR) the basic idea is to use ground- and satellite-based sensors to produce a complete macroscopic cloud characterization that is not available from satellite or ground data alone. First tests have shown that the stereo-camera retrievals can provide useful input for 3D radiative transfer simulations. A principle limitation to this approach is the restriction to mid- and high-level clouds because the stereo imaging of typical cloud-sized objects requires a distance of at least 2-3 km to the object. Radiative transfer results for the 08/10/1999 cloud data set in comparison with the real measurements are presented in Figure 6.8.

### 6.2.2 Application for NWP models

In a second application the cloud boundary data in the area of Zürich-Kloten will be used in an assimilation test to initialize the cloud water field of the operational MeteoSwiss NWP model aLMo (“alpines Lokalmodell”). Operationally, the aLMo model is run on a 7 km x 7 km grid. For the Cloudmap2 tests, MeteoSwiss in collaboration with ETH plans to run the non-hydrostatic model on a extremely high resolution 50 m x 50 m grid.

The satellite-based stereo cloud-top heights and winds can also be used for NWP model validation. Instead of comparing the total cloud cover of each model grid cell with a satellite-based cloud mask (e.g. MeteoSwiss project VENUS), we have begun to compare the full three-dimensional CLoud Content (CLC) field with our stereo results. The diagnostic CLC field provides an estimate...
of the percentage of cloud cover within each grid cell and it is derived using a combination of temperature, relative humidity and cloud water content. For the aLMo CTH map (Figure 6.9 left) the height values correspond to the center height of the top model layer that still contains some cloud fraction over a certain threshold (e.g. 10%). Instead of analyzing the CTH map, one can also extract vertical profiles of cloud content (CLC) and horizontal wind speed and direction for specific comparison locations (Figure 6.9 right).
Chapter 7

Conclusions and Outlook

7.1 Conclusions

Stereo mapping of clouds with modern photogrammetric methods is a valuable measurement technique for macroscopic cloud property retrieval, as has been shown throughout this study. The development of a stereo system based on commercial digital CCD cameras demonstrated how such a system could complement existing measurement instruments with additional information on the current cloud field, which can be quite important for nowcasting and short-range forecasting. With careful calibration and a precise matching algorithm, the system is capable of attaining height accuracies of a few meters (low clouds, 2-3 km) to about 100-150 m (high clouds, 10-12 km), depending on the actual cloud-base height. Looking at time series, the system can show the evolution of the cloud-base height for a special sky location over a given time period, similar to the well-known ceilometer profiles. In contrast to the ceilometer these cloud-base measurements contain additional information on the height range within the FOV as well as providing a visual impression of the cloud situation to the forecaster.

As for any optical system, the technique is not suited for operation in rain and snow when the use of microwave instruments (e.g. 94 GHz cloud radar) is the appropriate solution. During night, cloud detection is possible with longer exposure times, but due to cloud motion accurate results are difficult because of smearing of cloud structures in the longer exposure images. The use of a thermal infrared camera system or a cooled CCD system is certainly more appropriate at night. Given the environmental factors in the field, periodic recalibration of the ground-based cameras was necessary. With the star calibration method that we presented, recalibration was possible within minutes during every clear night.

In the ground-based analysis, seven cases that represent all major cloud situations were presented. The measurements were acquired at Mels, Switzerland, in October 1999 as part of the Mesoscale Alpine Programme SOP and at Zürich-Kloten airport in September 2001 and April 2002. To provide a quantitative evaluation of matching quality, the computed DSM was compared
with reference data. As described in the study, the best validation of the results with respect to the matching was comparison with manual, or semi-automatic, measurements. While texture enhancement is not absolutely necessary for well-defined cloud structures, preprocessing with the Wallis filter is recommended for most other cases, especially with stratus-like cloud layers or images with different radiometric characteristics. The use of more than two cameras can facilitate the derivation of approximate values, improve matching reliability and guarantee the simultaneous mapping of low and high clouds. While known non-cloud objects (e.g. sun occultor) can be removed in point selection, unknown disturbing objects (e.g. dust particles) that should not be matched can cause significant errors in the final cloud DSM. Therefore, quality control has to detect not only wrongly matched cloud points but also inadvertently matched image imperfections. Comparisons with other meteorological data (e.g. radiosonde, lidar, ceilometer, IR camera) have shown a good correspondence for the analyzed cases. The most accurate comparison instruments were the four ceilometers next to our camera locations at Zürich-Kloten airport, given that there were no cloud radars or high-resolution Doppler lidars installed in Switzerland.

Besides the obvious benefits, several limitations of our new stereo camera system have to be considered. First, the optical system is not suited for operation in rain and snow, as mentioned above. Second, the stereo images have to contain enough cloud structures for matching, which is problematic for some stratus cases or for optically thin cirrus. Third, the retrieved cloud-base heights are accurate estimates for the height of the matched cloud features, but these cloud features do not necessarily correspond with actual cloud boundaries. For most clouds, however, the stereoscopically matched features are a good proxy for the bottom boundaries of the clouds because most clouds become optically thick within a few hundred meters from their boundaries. In conclusion, the stereo camera system can retrieve accurate values of cloud-base heights for most cloud situations with relatively small errors from the matching and orientation. However, there are still large uncertainties due to the problem of object definition in the case of clouds.

In the satellite-based analysis stereo CTH and CTW retrieval principles from ATSR2, MISR and ASTER stereo pairs and triplets were explained. The preprocessing and matching parameters for each sensor, as well as the data characteristics of each instrument, were described. Besides an optimal base-to-height ratio, accurate georectification algorithms and sub-pixel accuracy in matching, accuracy in retrieved stereo cloud-top heights is largely influenced by the accuracy of the retrieved cloud motion field used for the CTH correction. This motion error is introduced due to non-synchronous acquisition of different views in stereo pairs and triplets. The time interval between subsequent views varies between about 40 s for MISR to 130 s for ATSR2. The large effect of motion inaccuracy on the order of 5 m/s was presented. As the cloud-top height error due to cloud motion is only dependent on the along-track wind component, correction amounts can vary significantly over the image from nearly no correction, if the wind direction is in cross-track direction, to up to 3-4 km for along-track wind speeds of 35-40 m/s. It is, therefore, important to consider these errors introduced by the wind and to correct for them with corresponding cloud motion data. We have developed a cloud motion correction method based on the new Meteosat-
6 10-minute Rapid Scans, operational since September 2001, with first tests on the Meteosat-6
5-minute Rapid Scan data acquired during MAP in autumn 1999. High-temporal resolution geo-
stationary cloud motion information has the advantage that it can be directly applied to correct
the extracted y-parallaxes for the along-track cloud motion component. Conventional wind mea-
surements and NWP winds have the disadvantages that the cloud height level has to be known
a priori and that wind and cloud motion do not always correspond to each other, especially in
mountainous terrain. As an extremely interesting validation option, it was shown that, by chance,
the cloud motion error for the MISR AN-AF and ASTER stereo CTHs is approximately the same,
independent of the actual cloud height and cloud motion. Therefore, the accuracy of MISR AN-AF
matching could be evaluated independently of artifacts due to the subsequent wind correction.

CTHs extracted with stereo-photogrammetric methods were claimed to be particularly valuable
insofar as they do not rely on meteorological data, which is not strictly true when cloud motion
has to be included. Therefore, other possible satellite-based stereo configurations are described
that allow cloud-motion-error-free stereo CTH retrieval (e.g. two geostationary satellites) or si-
multaneous CTH and CTW estimation (e.g. MISR multiview approach). For the MISR multiview
approach triplets from non-symmetric views have to be extracted. Matching statistics from the
various camera combinations indicated that the correspondences between non-adjacent cam-
eras (e.g. AN, BF and DF as used for the motion retrieval in the operational NASA JPL L2TC
product) can be quite tricky because the cloud objects have changed their shapes, or even dis-
appeared, during the delay between the two views. While the matching success rate is about
95% for adjacent cameras, it decreases to about 78% between the nadir and outermost DA/DF
cameras. We demonstrated that the success rate can be improved with subsequent matching
of the same points view-by-view by transforming the results of the former view combination into
approximate values for the next view combination.

The case studies with coincident satellite- and ground-based measurements illustrated validation
of satellite-based cloud-top height retrievals for vertically thin clouds with ground-based imagers.
Ground-based stereo camera systems also map smaller scale cloud features which are not or
only hardly mapped within satellite-based images and which can be important for regional now-
casting. The coincident ground- and satellite-based cloud data products from April 2002 will be
further exploited in two different model applications (DLR, MeteoSwiss) within Cloudmap2. To-
gether with the experiences from other ongoing cloud research projects on the assimilation of
existing and new in-situ, ground-based and satellite-based cloud data into NWP models, it will
significantly improve our understanding of cloud parametrization and representation in numerical
weather prediction and global climate models.
7.2 Outlook

With the rapidly decreasing prices on the digital camera market, the recent launch of new satellite-based stereo instruments (e.g. MISR, ASTER, Envisat-AATSR) and the advances in modern photogrammetric analysis methods, stereo-photogrammetric mapping of clouds can play an important role in the improvement of cloud boundary detection in the future. Ground-based camera systems in stereo setup can be used next to other cloud height measurement instruments (e.g. ceilometer, cloud radar, Doppler lidar) for comparison and calibration. As none of these instruments is the “perfect” instrument under all cloud and weather conditions, such comparison studies can help to further identify the strengths and weaknesses of each system and how they can complement each other in a composite observational network.

In this context it would be interesting to evaluate how operational whole-sky imager systems (e.g. WSI, TSI) are suited for stereo measurements of clouds. A new campaign would ideally take place at the ARM SGP site where many sophisticated cloud measurement instruments are installed (e.g. cloud radar, Raman lidar, ceilometers). It would further allow us to test the newest system extensions, planned by Janet Shields, to project laser tie points onto the clouds for a faster and more reliable derivation of first approximations in the matching (Shields, 2003). Another interesting research subject is the use of different spectral channels for the camera measurements (e.g. IR stereo cameras). As we have seen from the multi-spectral stereo analysis of the ATSR2 images, the results in the various spectral channels can be significantly different, especially in multi-layer cloud situations.

On the algorithmic side, the most important point is to work with a robust matching technique. Our hierarchical approach with the MPGC LSM software showed to be usable for the task of cloud matching. Improvements are possible (a) in the automatic setting of the matching parameters (e.g. patch size and shape) with a pre-analysis of the cloud field or (b) in the MPGC LSM implementation itself by including multi-patch matching (Gruen, 1985a; Gruen and Li, 2002). An important post-processing step, which was not treated further in this thesis, is the automatic segmentation and interpretation of the extracted three-dimensional information. For example, classification of the points into distinct cloud objects, or layers, is important for more realistic modelling and visualization of the clouds. The segmentation could be facilitated by using the information from the retrieved cloud DSM. Separation of extracted edges into edges that are actually cloud boundaries and edges which only describe a change of the optical properties within a cloud would be a second useful post-processing step. Given the different methods of cloud classification and region extraction, tests with regional matching algorithms could be performed to provide additional information for subsequent cloud layer segmentation. Looking at image sequences, new matching methods could be tested, e.g. active contours and level-set methods, to solve the additional problems of shape changes or even appearance/disappearance of cloud features. For an operational use of the cloud-adapted matching procedure the single processing steps will have to be combined into an overall processing chain, which would then allow to automatically determine a 3D
cloud-base/-top geometric model from the raw multi-view images without any user intervention. The most problematic extensions are hereby probably the automated adaptation of the various processing parameters throughout the processing chain to the current cloud situation.

Accurate satellite-based retrievals of cloud-top heights depend strongly on a precise sensor model. In another study at our Institute the MISR stereo accuracy potential will be further evaluated with a new general linear-array sensor model and subsequent multi-photo geometrically constrained LSM matching. As shown in this work, our unconstrained hierarchical matching approach with subpixel accuracy produced accurate MISR CTH results. Another effort could be undertaken to improve the matching process between images with longer time delays where similar congruence problems, as in the tracking of image sequences, can be identified. Cloud motion error correction with geostationary CTW data will be significantly improved with the recent launch of Meteosat Second Generation (MSG). So far, spectral differences present in the CTH results were not adequately reproduced in the retrieved CTW data from Meteosat-7 or from Meteosat-6 Rapid Scans. With the new spectral channels and higher spatial resolution of MSG, this problem will be minimized and the MSG data will provide highly valuable CTW data as correction data for AATSR multispectral CTH results and as validation data for the MISR simultaneous CTH/CTW retrieval algorithm. Further improvement of the combined MISR CTH/CTW product will give valuable input data to NWP models, as height assignment of geostationary tracked cloud motion winds is still an open issue (Niels Bormann, personal communication). It will also be interesting to discuss the design of next-generation satellite-based stereo sensors (e.g. successor sensor of MISR) and how large cloud motion influences could be minimized with alternative stereo configurations.

As shown throughout this thesis, stereo measurements have the advantage that they depend only on basic geometric relationships of observations of cloud features from at least two different viewing angles and on the texture of these cloud features, while other cloud height estimation methods are dependent on knowledge of additional atmospheric parameters, like cloud emissivity, ambient temperature or lapse rate. Both ground- and satellite-based stereo measurements can, therefore, nicely complement other retrieval methods and advance our understanding of cloud boundary characteristics and their use in nowcasting and cloud modelling.
Bibliography


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Appendix A

Radiosonde plots
Figure A.1: MAP sounding, Diepoldsau, launched 08-10-1999 12:00 UTC.
Figure A.2: MAP sounding, Masein, launched 13-10-1999 12:00 UTC.
Figure A.3: UK MetOffice sounding Larkhill (03743), launched 28-06-2000 12:00 UTC.
Figure A.4: MeteoSwiss sounding, Payerne, launched 03-08-2000 12:00 UTC.
Figure A.5: UK MetOffice sounding Larkhill (03743), launched 13-06-2001 12:00 UTC.
Figure A.6: ETH sounding, ETH-Hönggerberg, launched 29-09-2001 15:00 UTC.
Figure A.7: ETH sounding, ETH-Hoenggerberg, launched 12-04-2002 10:00 UTC.
Figure A.8: MeteoSwiss sounding, Payerne, launched 12-04-2002 12:00 UTC.
Figure A.9: MeteoSwiss sounding, Payerne, launched 19-04-2002 12:00 UTC.
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