Cloud Mapping from the Ground: Use of Photogrammetric Methods

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Abstract
Within the European Union (EU) project Cloudmap, a ground-based sky imager system consisting of two commercial digital CCD cameras with wide-angle lenses has been established which can theoretically be used to derive various macroscopic cloud parameters (cloud-base height, cloud-base wind, cloud amount). In this paper, we present the method to calculate a digital surface model (DSM) of the cloud base. It includes both the precise determination of the interior and exterior orientation of the cameras as well as the automatic derivation of the cloud-base heights using modern photogrammetric algorithms.

The presented measurements were taken during the Mesoscale Alpine Programme (MAP) in Switzerland in October 1999. The results from our own matching software and from commercial photogrammetric systems were validated with semi-automatically measured points and compared with visual observations, lidar, and radiosonde data from the MAP Composite Observing Network and satellite-based cloud-top heights from ERS2-ATSR2. The potential of the system to provide very accurate areal cloud-base height data was shown. This is important for the objectives of the EU project Cloudmap2, where it is planned to assimilate various cloud parameters, including cloud-base height, into cloud and high-resolution numerical weather prediction (NWP) models.

Introduction
Clouds play a pivotal role in the interaction between the Earth's climate and anthropogenic inputs, particularly from the increase in greenhouse gases. Therefore, accurate global measurements of the relative location, distribution, and character of clouds (which have a strong impact on both the total incoming radiation at the surface and the reflected radiation above the cloud field) are necessary as described in the rationales of the European Union (EU) projects Cloudmap and Cloudmap2 (Cloudmap, 2001; Cloudmap2, 2001). For receiving global coverage, satellite-based methods have to be used, but they have to be calibrated and validated with ground-based measurements; furthermore, the global numerical weather prediction (NWP) and climate models are refined by higher-resolution regional models whose initial conditions have again to be updated by ground-based measurements. In Cloudmap, three independent ground-based validation instruments were operated within various measurement campaigns: cloud radars, airborne lidar profilers, and stereo photogrammetric systems such as the one described in this paper. While the first two instruments are also used to derive microphysical cloud properties, our instrument was tested for delivering very accurate areal data of the 3D cloud base, which are necessary for weather and climate models, as described later in this paragraph. Cloud-base height (CBH) is one important factor in determining the infrared radiative properties of clouds. However, cloud-base heights are not well known from the existing observation networks, except at a very few places around the world which are equipped with high-cost instruments (see Table 1). At most climate stations of the national networks, cloud macroscopic properties—mainly cloud cover, cloud depth, and cloud-base height—are still visually observed. Mainly at airports, ceilometers are in operational use to measure the cloud-base height automatically and continuously in addition to the visual observations. It is well recognized today that the infrequent, spatially not equally distributed, subjective, and too sparse point observations of clouds do not meet the requirements of numerical weather prediction (NWP) and global climate models (CCM). The data from our ground-based stereo imager system will in this context nicely complement existing instruments and observations with very accurate, spatial, and frequent 3D cloud-base heights which should be suitable for the meteorological models.

Within the EU project Cloudmap2 (Cloudmap2, 2001), we are currently working on gaining knowledge about the requirements of temporal frequency, spatial coverage, and accuracy for cloud products to be used as assimilation data into NWP or specific cloud models. These new requirements are certainly higher than the operational user requirements defined in the World Meteorological Organization (WMO) Guide to Meteorological Instrumentation and Methods of Observation, which state for CBH a vertical accuracy of 10 percent, a height range from 30 m to 30 km, but no specific numbers about time resolution or area coverage (Hans Roozekrans, personal communication). In particular, areal measurements or much denser networks will possibly be required.

Ground-based digital cameras in stereo configuration can help to fulfil some of the user requirements described above. Analog stereo images of clouds have been taken and analyzed for more than a hundred years (Koppe, 1986). It was shown that cloud-base height and cloud-base motion can be determined from such systems and used as validation data for satellite-based cloud properties (Bradbury and Fujita, 1968). Nevertheless, such an analog system is only useful for research purposes; any operational use of the analog images was not possible due to the enormous amount of time to analyze a single time step by first scanning the images and then finding the corresponding points by manual measurements. Digital systems have the major advantage of reducing the processing time significantly, down to less than an hour, which gives them the potential of deriving the cloud parameters in near real time. Practical fieldwork with monoscopic digital whole-sky imager systems (WSI) (Shields et al., 1999) was first performed at various Atmospheric Radiation Measurement (ARM) Program sites...
(Stokes and Schwartz, 1994). Today, other commercial digital whole-sky imager systems in monoscopic mode have become available, which are less expensive than the WSI, but which are not radiometrically or geometrically calibrated (e.g., TSI (Yankee, 2001)). Allmen and Kegelmeyer (1996) used a stereo setup of two WISs to automatically derive cloud-base heights; due to the large base chosen and due to inaccuracies of the exterior orientation, the matching of the stereo pairs was very difficult. Furthermore, the matching process was much slower than today because of slower computer processors (Janet Shields, personal communication). We show in this paper that a stereo setup of two or more digital cameras makes sense to be used as an operational instrument in research campaigns (e.g., ARM) or even in the network of a National Weather Service, to complement existing observations and instruments. Recent developments in the digital camera market (lower prices, higher resolution and accuracy) are currently leading at National Weather Services (e.g., Meteo Swiss and the German Weather Service DWD) to a revival of the idea of photogrammetric cloud observation station networks which was in discussion more than 100 years ago during the International Year of the Clouds 1896 (Koppe, 1896). The improvements on the algorithmic side to solve the correspondence problem automatically, faster, and more reliably with modern matching methods could lead one to consider the installation of more than one camera at some sites in order to derive quantitative cloud information such as CBH or cloud-base motion. This shows a further advantage of acquiring data from a ground-based photogrammetric system: such data are easier to visually interpret (and to link with the current synoptic situation) by a forecaster than are the point measurements of the cloud base from ceilometers, lidars, or radars.

The two main research questions addressed in this paper are (1) the establishment of an imager system based on inexpensive off-the-shelf components (including the choice of an optimal sensor and the description of an optimal geometric arrangement of the two or more cameras), and (2) the development of an automatic cloud-adapted matching algorithm to derive the DSM of the cloud base.

### Camera System and Experimental Setup

To evaluate the ability of a photogrammetric system to measure cloud properties and to validate cloud products derived from satellites within Cloudmap, a ground-based sky imager system consisting of two commercial digital CCD cameras with wide-angle lenses was developed.

The choice of an appropriate digital camera and sensor is crucial in this context. On the camera side, the following criteria should be considered: stability of the interior orientation (chip, focal length), the possibility to control all camera functions from a laptop computer, the maximum exposure time (at least 30 seconds), the performance of image storage and transfer, the data format, the power supply requirements, and the cost. On the sensor side, the spatial, spectral, and radiometric resolution of the chip as well as the dynamic range and the noise characteristics should be considered.

For our first prototype, described in this paper, the Kodak DCS460 camera was chosen. This camera fulfilled most of the criteria mentioned above except that longer exposure times had to be released manually. At the time of evaluating the possible systems, most cameras did not offer control functions from a laptop computer or exposure times longer than 1 to 2 seconds. The number of cameras was limited to two because only two cameras of this type were easily available. A main reason to use a new camera (Fujifilm S1 Pro) in future measurements is the fact that the Kodak DCS460 camera unfortunately did not fulfill another very important criteria, stability, which was not anticipated in advance: a movement of the chip occurred during the measurement campaign and was possible because the chip is only attached along one chip border (see section 3 on Camera Calibration).

In the following, we describe the camera system, the sensor, the measurement campaign, and the camera location setup.

### The Camera System

Each camera system (Figure 1) consists of a Kodak DCS460 color digital CCD camera connected via an SCSI interface to a laptop.

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Table 1. Comparison of Different Instruments for Measuring CBH

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Visual observation</th>
<th>Radiosonde</th>
<th>Ceilometer</th>
<th>Doppler lidar</th>
<th>Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Whole sky</td>
<td>Point³</td>
<td>Point²</td>
<td>Point²</td>
<td>Point²</td>
</tr>
<tr>
<td>Frequency</td>
<td>Every 0.5–6 h</td>
<td>Every</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>Range</td>
<td>&lt; max. visible</td>
<td>6–12 h</td>
<td>&lt; 10–12 km</td>
<td>&lt; 10–12 km</td>
<td>&lt; 15 km</td>
</tr>
<tr>
<td>CBH accuracy</td>
<td>20–30% of CBH</td>
<td>2% of CBH</td>
<td>2% of CBH</td>
<td>2% of CBH</td>
<td>&gt; 60 m³</td>
</tr>
<tr>
<td>Costs</td>
<td>$200 per launch⁴</td>
<td>$35,000</td>
<td>$700,000</td>
<td>$1,000,000</td>
<td>$800,000 per camera station⁷</td>
</tr>
<tr>
<td>Additional cloud parameters</td>
<td>Cloud amount,</td>
<td>Cloud-top</td>
<td>Microphysical properties</td>
<td>CTH, microphysical properties</td>
<td>Cloud amount, cloud base motion</td>
</tr>
<tr>
<td>Complexity</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>Potential for automated</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹A difficulty is the fact that the point measurement is not vertically above the launch location but needs to be calculated from the trajectory.
²Depending on the lens used. With our lens, an area of about 1.5 "CBH" is covered.
³Above, the cloud-base height is estimated using the cloud type and appearance (accuracy even worse).
⁴Depending on cloud type (the base of water clouds is not so sharply defined as the base of ice clouds).
⁵See error calculation in section on Measurement Campaign and Site, Equation 2 (matching accuracy) and section on Derivation of Reference Data from Matching and Quality Analysis of Matching Methods (orientation data accuracy).
⁶Not included: initial costs for ground station (antenna, receiver, etc.) which are in the range between $100,000 (research station) up to $700,000 (operational station).
⁷This price includes costs of the Fujifilm S1 Pro camera, the heated box, the tripod, and the camera control laptop. Depending on environmental conditions (e.g., mountain station) and operability without daily maintenance, further costs have to be added.
computer with precise time information from a GPS receiver or radio clock. The shutter release is controlled from the computer, with use of the Kodak PDC-SDK library. The camera is mounted on an adapted theodolite tripod which allows precise horizontal adjustment of the camera with leveling screws and with the use of an electronic leveling instrument on the lens. For the measurements within Cloudmap2, the camera is no longer mounted directly on the tripod, but is protected within a heated box (1 to 2°C above air temperature to avoid condensation on the image sensor) which is then mounted onto the tripod. The approximate adjustment of the azimuth parallel to the baseline has been done—due to the distance to the other camera—with a small telescope. The tripod has a moving sun occultator (which can be used against image blooming caused by the sun; partly visible at the upper right of Figure 6a) and a small heating device to avoid condensation on the CCD sensor or storage chip during longer imaging series and during night image acquisitions. A Nikon 18-mm wide-angle lens with a nominal viewing angle of 100° was used.

Because the system is a prototype for research campaigns, the mechanical details of the system are still subject to improvement. Currently, an extension is in work to close a cap over the camera lens automatically if it starts to rain/snow. Under these conditions, no measurements are possible with this system, just as with any other instruments operating in the visible spectrum.

The Kodak DCS460 Sensor
The camera's CCD array is a KAF-6300 with 3072 by 2048 pixels, each 9 by 9 μm, with a Bayer color filter (Bayer, 1976). In the Kodak image processing software, the six rows and columns near the edge of the array are discarded. The RGB values (8-bits per color) of the remaining 3060 by 2036 pixels are calculated with a 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 (10pA/cm² at 25°C) and especially influences the long exposure night images when using stars for exterior orientation determination (see the section on Star Calibration). Therefore, images were taken at various exposure times between 0.002 and 240 seconds with the lens cap closed for each camera in order to analyze the dark current noise. It was shown that the dark current noise is camera-dependent, spatially variable, temporally stable, and increases with longer exposure times.

Measurement Campaign and Site
The data acquisition took place during the Special Observation Period (SOP) of the Mesoscale Alpine Programme (MAP). MAP is an international research initiative devoted to the study of atmospheric and hydrological processes over mountainous terrain. It aims towards expanding knowledge of weather and climate over complex topography (MAP Implementation Plan, 1999).

Our two camera locations were situated at Mels within the SOP target area “Rhine Valley,” Switzerland (Figure 2), separated horizontally by 850 meters, and were intervisible; the baseline direction was parallel to the valley, from northwest to southeast. The choice of an appropriate base length for cloud mapping is difficult because of the wide height range of clouds (up to 15 km). The overlapping area of a stereo pair is calculated as

\[
\text{overlap} = \left(1 - \frac{bc}{2xh}\right) \times 100\% \tag{1}
\]

where \(b\) is the base length [m], \(x\) is the dimension of the sensor in the baseline direction, \(c\) is the focal length, and \(h\) is the cloud height [m above ground]. For our setup with \(b = 850\) m, \(c = 18\) mm, and \(x = 27.54\) mm, overlapping starts at a cloud height above 280 m at 3.5 km; the overlap area is 92 percent and at 10 km 97 percent. In addition, shorter base lengths (\(\leq 1\) km) have the advantage that 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 longer base lengths: while lower clouds require shorter base lengths to get a reasonable overlapping area, the higher a cloud is situated, the greater should be the base length due to the height accuracy \(s_z\); i.e.,

\[
s_z = \frac{h^2}{bc} \times s_{px} \tag{2}
\]

where \(s_{px}\) is the parallax measurement accuracy [m].
For our base length of 850 meters, an assumed parallax measurement accuracy of 1 pixel (9 μm), and cloud heights of 3.5 km and 10 km above ground, we obtain height accuracies of 7.2 m and 58 m, respectively.

For future operational applications 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 rotation and change of focal length) or the use of more than two cameras with different base lengths should be evaluated.

Camera Calibration

Interior Orientation
The interior orientation parameters were determined using a close-range photogrammetric reference field measuring 4.2 by 2 by 1.2 m with 77 signalized and 20 coded points and located at the Institute of Geodesy and Photogrammetry (IGP), (ETH) (Figure 3). For each camera, 15 images were taken: from five camera stations (left high, left low, center, right high, right low) at three different roll angles (-90°, 0°, +90°). Before the calibration process, the CCD chip was fixed with respect to the camera back so that no movement of the chip should occur during the calibration and during the fieldwork. The instability of the Kodak DCS CCD arrays due to the mounting of the chip only at one side against shock influence is described in Shortis et al. (1998).

The camera model parameters were calculated simultaneously with camera orientation data and 3D object point coordinates, employing a self-calibrating bundle adjustment. Ten additional parameters were used to model systematic errors (Brown, 1971): three parameters of interior orientation (focal length offset dc, and principal point coordinate offsets dxp, and dyp), five parameters modeling radial and decentering lens distortion (radial coefficients k1, k2, and k3) and decentering coefficients p1 and p2) and two parameters for a differential scale factor and a correction of the non-orthogonality of the image coordinate axes (Beyer, 1992). Table 2 lists the result of the calibration for both cameras. The differential scale factor, the non-orthogonality factor, and some of the lens distortion coefficients proved to be insignificant.

A second test-field calibration of both cameras made after the measurement campaign showed — despite the additional fixing of the chip — an instability of the principal point of both cameras of up to 0.15 mm in the x direction and 0.05 mm in the y direction.

Exterior Orientation from GPS, Calibration Flight, and Stars
The exterior orientation of both cameras has to be determined at the measurement locations. Because the cameras are horizontally mounted and the field of view includes only 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. Two independent sets of sky control points were established: during daylight, an airplane equipped with differential GPS flew along a specific flight pattern; during clear nights, stars could be seen in images with long exposure times and be taken as sky control points. In addition, the coordinates of both camera stations were measured with GPS units before the campaign. The operational Swiss GPS network stations at Zurich, Davos, and Pfänder were used as reference stations. In the following, the two methods — "airplane" and "stars" — are described in more detail.

Calibration Flight
To get artificial sky control points, a previously calculated flight pattern was flown by a Swiss Army KingAir aircraft. The flight lines were parallel to the baseline of the two cameras. The highest flight line was 4000 m above ground and the lowest flight line was 1000 m above ground. The flight lines were along the left and right borders of the images and along the middle. The DGPS antenna of the airplane was manually measured in every image. From the exact acquisition time of the image, the position of the point could be determined from the GPS calculation and could then be used as a control point. With a bundle adjustment (with fixed interior orientation parameters from the test-field calibration and station coordinates from static GPS), the orientation angles were estimated together for both cameras. The image residuals showed an accuracy better than 3 pixels across track, consistent with the poor manual measurement accuracy (due to the oblique viewing angle, the recognition of the plane and, even more, the position of the antenna was very difficult; see Figure 4), but showed an accuracy of no better than 10 to 15 pixels along track, caused by the error in the precise acquisition time (at a mean velocity of the KingAir of 100 m/s, ten pixels corresponds 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.

Star Calibration
An alternate method, with star images, was used to determine the exterior orientation angles. Additionally, the interior orientation parameters (the same ten parameter set as described earlier) of the camera were estimated, which is promising for longer measurement periods where the interior orientation, even of a theoretically stable camera, could eventually change over time. This second method is also more realistic for an operational sky imager network where recalibration of the orientation angles is probably necessary at regular time intervals. The sky images with long exposure times were taken during clear nights. When the exposure time is longer than about one minute, the paths of the brightest stars can be seen between the noise (Figure 5). Although the noise represents a sum of dark current noise and sky background (atmospheric scatter light, etc.), it can in this case, with very low sky background, be modeled as a dark current noise image alone, taken with a similar exposure time. It is important to use the raw 8-bit color array values directly, before any color interpolation, which are fortunately accessible from the Kodak camera (which is a major drawback of many other cameras). The enhanced star paths images were then further processed by a specialized software (Schildknecht, 1994) to identify the stars corresponding to the Position and
Proper Motion (PPM) star catalog. From the star positions, the orientation angles and the interior orientation parameters of both cameras were calculated using the same software package. The optimum exposure time is based on two factors: the detectability of the linear feature (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 assumed 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 $\pm 4^\circ$.

**Comparison of Orientation Parameters**

Interior and exterior orientation parameters are very important not only for accurate 3D point determination, but also because this information should be used in matching to limit the search space along epipolar lines (Baltsavias, 1991). To check the quality of interior and exterior orientation, well-defined points over the entire image were selected in the left image, and the distances of the epipolar lines from the true, manually measured corresponding points in the right image were calculated. The best results were achieved with the interior orientation values of the first test-field calibration and the respective exterior orientation determination using the aircraft (maximum epipolar line displacement of 4 pixels).

Apart from errors in orientation angle determination, the instabilities of the interior orientation of the DCS460 (mainly of the principal point; see the section on Interior Orientation) may have contributed to these inconsistencies. In future applications, a new camera (Fujifilm S1 Pro) will be used which is equipped with a stable chip, but was not yet available during MAP. For further campaigns within Cloudmap2, the same IGP test field will be used for the calculation of the interior orientation of the cameras; the exterior orientation will be determined with GPS (camera position coordinates) and with star images (orientation angles, control of interior orientation).

**Calculation of Cloud-Base Height**

To calculate CBH automatically, different image processing algorithms, especially image matching, have to be applied. The same algorithms can also be used for derivation of cloud motion by matching corresponding features in image sequences. At the IGP, many such algorithms have been developed over the last 20 years and have been employed in the matching of various objects. They include, among others, both area-based and feature-based matching methods, the latter employing point or linear/edge features. Our approach within Cloudmap was to first use and test existing methods, including commercial matching software, and try to adapt them where necessary to model or reduce special problems encountered with clouds. Such problems include, in some cases, the very different appearance of clouds due to the varying viewing angle of the cameras and illumination conditions, semi-transparent surfaces (e.g., with cirrus clouds), large discontinuities in object space between surfaces that appear to be adjacent in the image (clouds and sky, multilayered clouds) or surface discontinuities within one cloud, a lack of texture and saturation, and a lack of clear cloud boundary definition. The use of existing matching algorithms was aiming at achieving a high success rate, accuracy, and reliability. Aspects of processing speed were not considered at this stage, although this is clearly of importance if a system has to be used operationally and process large datasets. The selection of matching methods is dependent on the number of cameras that are imaging one object. With three or four cameras, fast and reliable matching procedures have been used at the IGP (Maass, 1992) using point features and geographically consistent triplets or quadruplets of such features. However, only two cameras could be used in the MAP campaign. Thus, for these matching tests, we decided to use (1) existing commercial digital photogrammetric systems, because their use and performance in the task of cloud matching was unknown, and (2) least-squares matching employing geometric constraints derived from the known exterior and interior orientation of the sensors, because this method fulfilled to a large extent the requirements of high accuracy, success rate, and reliability. During the tests, some limitations of the previous matching systems (see below) led us to also try edge-based matching, but the results of the latter method, presented here, are only preliminary. The commercial photogrammetric systems used were DPW 770 of LHS, Match-T of Inpho, used also in the 2/1 and DAT/EM systems, and Virtuozo, covering the most widely used and better performing commercial systems. A description of these systems and some evaluation of their matching performance is given in LHS (2001), Inpho (2001), Supersoft (2001), Baltsavias et al. (1996), and Baltsavias and Kaeser (1998). To allow an objective comparison of the results of the various matching systems, the same starting conditions, i.e., known interior and exterior orientation and image preprocessing, should be used. However, this was not always possible as will be explained below.

**IGP Methods for Cloud Matching**

The main IGP matching method used was the Multi-Photo Geometrically Constrained Matching Software (MPCC) package.

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**Table 2. Additional Parameters and Their Standard Deviations as Determined from the Test-Field Calibration**

<table>
<thead>
<tr>
<th>Camera</th>
<th>$c$ [mm]</th>
<th>$x_p$ [mm]</th>
<th>$y_p$ [mm]</th>
<th>$k_1$ [mm$^{-1}$]</th>
<th>$k_2$ [mm$^{-1}$]</th>
<th>$p_1$ [mm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera 1</td>
<td>18.614453</td>
<td>0.305271</td>
<td>-0.269040</td>
<td>-2.983e-04</td>
<td>5.940e-07</td>
<td>2.679e-05</td>
</tr>
<tr>
<td></td>
<td>$\pm 1.338e-03$</td>
<td>$\pm 6.241e-04$</td>
<td>$\pm 1.766e-03$</td>
<td>$\pm 7.614e-07$</td>
<td>$\pm 4.587e-09$</td>
<td>$\pm 1.576e-06$</td>
</tr>
<tr>
<td>Camera 2</td>
<td>18.162422</td>
<td>0.279594</td>
<td>0.069326</td>
<td>-2.370e-04</td>
<td>5.223e-07</td>
<td>7.990e-07</td>
</tr>
<tr>
<td></td>
<td>$\pm 1.064e-03$</td>
<td>$\pm 4.690e-04$</td>
<td>$\pm 1.595e-03$</td>
<td>$\pm 7.990e-07$</td>
<td>$\pm 5.218e-09$</td>
<td>$\pm 1.286e-06$</td>
</tr>
</tbody>
</table>

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**Figure 4.** KingAir on three flight levels: left: 1000 m, middle line; center: 2000 m, flight line along right border; right: 4000 m, flight line along left border.

**Figure 5.** Left: star path and dark current noise, center: dark current noise, right: difference image.
(Baltsavias, 1991), which is based on least-squares-matching (Grün, 1985). With the geometric constraints, the search space is restricted along epipolar lines, thus increasing the success rate of the matching and reducing matching problems. The geometric constraints are implemented as weighted observations, thus allowing their relaxation 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 template) and are found in other overlapping images (called patches). The similarity between the template and the patches is achieved by using an affine geometric transformation and a two-parameter radiometric transformation. Non-determinable affine parameters can be excluded from the estimation process and/or simpler determinable transformations can be employed (conformal, two shifts and one rotation, only two shifts). Both grey values or any functions of them (e.g., grey level gradients) can be used in matching, making this method a hybrid one, i.e., both area-based and feature-based. The method provides different quality criteria which can be used in quality control and automatic detection of blunders. The main steps used in MGCM are:

- image preprocessing;
- feature extraction in one image, rough cloud object segmentation;
- hierarchical matching using image pyramids; and
- quality control to automatically find and exclude gross errors.

**Preprocessing**

For matching, the red channel (8-bit) was used because of its better contrast compared with the other channels. Many systems cannot process imagery with more than 8-bit, and the Kodak DCS460 does not deliver real 12-bit data anyway due to the mosaic color sensor. The dark current was not subtracted as for the star images because of the small exposure times of 1/1000 to 1/250 s. To improve matching, a Wallis filter was used (Wallis, 1976). This leads to a radiometric equalization of the matched images and contrast enhancement, i.e. more texture (see Figure 6). Wallis is an adaptive, local, nonlinear filter, which has been extensively used at the IGP in image pre-processing for matching (see, e.g., Baltsavias (1991) and Baltsavias et al. (1996)). This preprocessing was used for all matching systems.

**Feature Extraction**

With MGCM, the points to be matched are generally selected along edges that have a sufficient intersection angle with the epipolar lines (e.g., at least 10°). Such points enable both high matching accuracy and avoidance of multiple solutions when edges are parallel to epipolar lines. Interest operators selecting features with good 2D texture can also be used but lead to a smaller number of match points. However, this number could be sufficient for CBH determination. Thus, various point and edge operators have been tested. All of these interest operators have to use dynamic thresholds (varying over the image) because the operators can be very different in various cloud regions. Such thresholds were implemented in the algorithms of the used interest operators.

Two different interest operators were used for point extraction, the Förstner operator (Förstner and Guld, 1987) and the Harris operator (Harris and Stephens, 1988). Both have been extensively used in photogrammetry or computer vision with good results. Figure 7 shows the resulting points from the Förstner operator for the 08 October 1999 image. The choice of the optimal parameters was always a trade-off between getting enough points and avoiding points within the sky. The latter could be due either to small very faint clouds or to noise in the images. Another possibility for avoiding points within the sky before matching is the use of a cloud mask (various methods for deriving a cloud mask are described below); only points within the cloud mask are then used in the further matching process. The advantage of the Förstner operator compared to the Harris operator is the possibility to extract points with good 2D texture or only along edges with a certain angle to the epipolar lines or both. The latter option would lead to denser match points and was preferred. With our camera setup, the epipolar lines were horizontal over the whole image so that distinct points at non-horizontal edges (intersection angle to epipolar lines greater than 10°) and 2D texture points were selected for matching.

As a segmentation method previous to the matching, a cloud mask was calculated for the template image. Most cloud mask algorithms for sky camera systems work with the red/blue ratio and a dynamic threshold which is adapted according to the camera location and date of image acquisition (Janet Shields, personal communication). Our second approach for deriving a cloud mask uses an existing image sequence and assumes that the radiance values within non-cloud parts are more or less stable during short time intervals while the values within clouds are constantly changing because of the cloud motion. Figure 8 shows the result of the sequence-based cloud mask; it has its disadvantages within larger cloud objects (the cloud interior may appear stable over short image sequences) or for stable/slow moving clouds, but can be a useful source of additional information for more accurate cloud mask estimation methods. The cloud masks thus derived were used to filter out points selected by the Förstner operator in non-cloud areas.

**Hierarchical Matching**

One problematic step for all matching algorithms is the determination of first approximations for the positions of corresponding features in the overlapping images. Currently, almost

![Figure 6. Altocumulus cloud (a) in the original image and (b) after the Wallis filtering.](image_url)

![Figure 7. (a) Original image. (b) All points from Förstner operator (shown in light grey).](image_url)
all methods, including all commercial ones, use multiple pyramid levels for derivation of approximations. MCGM also uses pyramids to reduce the maximum parallax to within 2 to 3 pixels, which corresponds to the usual convergence radius of the least-squares matching (LSM) algorithm.

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 at hand and thus also the number of needed pyramid levels are either predetermined or fixed empirically or could be determined automatically by starting with many pyramid levels, finding approximately the maximum parallax after matching in the highest or even lower levels, and then restarting from the level that satisfies the convergence requirements of the employed matching algorithm. In these tests and due to the possible very large parallax range, a few manual measurements were performed to estimate approximately the maximum parallax. However, as mentioned earlier, this process can be fully automated. Furthermore, a first estimate of the maximum parallax can be derived from the maximum parallax of the previous stereopair processed, because consecutive images of the recorded sequence had an overlap of 96 percent (30 seconds time difference). Because MCGM needs quite good approximations of 2 to 3 pixels, this may lead to the necessity of using many pyramid levels, which on the other hand may lead to very small images, computational expense, fusion of discontinuous surfaces, and propagation of matching errors to lower pyramid levels. Thus, it is planned to use an existing algorithm or to develop an algorithm that has a larger convergence range and is potentially faster than MCGM for matching in the upper pyramid levels. Algorithms that will be tested include cross-correlation or an edge matching developed at the IGP (Zhang and Baltsavias, 2000).

Depending on the cloud height range, three to five image pyramid levels were used for the hierarchical matching procedure. In the current tests, a fixed set of matching parameters was used in all pyramid levels. Based on previous experience and some tests using supervised matching of manually selected features, the following parameters were chosen as optimum: patch sizes of 15 by 15 pixels (level 0 and 1), 13 by 13 pixels (level 2 and 3), and 11 by 11 pixels (level 4 and 5); use of grey levels for matching; use of three geometric parameters (two shifts and one scale); and use of decreasing weight for the geometric constraints towards the higher-resolution pyramid levels (because of the orientation inaccuracies; see the section on Camera Calibration). The use of constant matching parameters in all pyramid levels and even all match points at one level is not optimum. Critical parameters such as patch dimensions, orientation of template patch, and number and type of affine parameters should be adapted dynamically in order to ensure determinability of the affine parameters and avoidance of using a patch that extends over discontinuous surfaces. Thus, a new feature detection operator is currently under development which will automatically determine the optimum parameter set for each point with a patch analysis previous to the actual matching.

Quality Control

MCGM provides several statistical measures that can be used to detect and exclude gross errors, e.g., cross-correlation coefficient, a posteriori variance of unit weight from the least-squares adjustment, size of scales, shears and parallax, number of iterations, etc. None of these measures can safely detect all blunders without also excluding good points. A combination of these quality measures can provide a better diagnosis. 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 very poor value for a point, the point was excluded. These poor values (thresholds) were chosen conservatively, i.e., the aim was to exclude only large blunders which may distort the statistics mentioned below. Then, a relative test was performed. In this test, the thresholds are derived from the statistics of all match points and are expressed as functions of the mean value and the standard deviation of each criterion, e.g., the threshold for cross-correlation was defined as mean-N* standard deviation, with N usually set equal to 3. Instead of mean and standard deviation, robust statistics such as median and median absolute deviation from the median can be used. Such blunder detection tests have been used at the IGP in various matching projects. In all cases, they improve very significantly the results, although always some blunders will remain undetected and, on the other hand, some correct match points will be rejected. The tests lead to a rejection of a certain percentage of the match points, e.g., 5 to 25 percent, depending on the matching problems and the selection of the thresholds. Such tests are applied after matching in each pyramid level in order to avoid propagation of wrong results to the approximations derived for the next lower level.

Results

Table 3 shows the result of three selected stereo pairs: an altocumulus and two cirrus situations. The cases were chosen with respect to the MAP validation data available. For the 13 October 1999 case, the DSM points were manually grouped into the two distinct cloud layers in order to enable comparison to available validation data. The automation of cloud layer (or object) segmentation as well as the 3D modeling and cloud visualization are important tasks of Cloudmap2 which will be investigated in the near future.

Commercial Matching Software

Three commercial digital photogrammetric systems (Match-T, VirtuoZo, and DPW 770) were tested for the automatic derivation of CBH using matching. The interior and exterior orientation, as well as the affine transformation from pixel to photo

<table>
<thead>
<tr>
<th>Date, Time</th>
<th>Cloud type</th>
<th>Mean cloud height [km]</th>
<th>Cloud height range [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>08 Oct 1999, 10:58</td>
<td>Altocumulus</td>
<td>4.0</td>
<td>3.8-4.2</td>
</tr>
<tr>
<td>13 Oct 1999, 10:16</td>
<td>Cirrus, two layers</td>
<td>8.0</td>
<td>7.8-8.1</td>
</tr>
<tr>
<td>20 Oct 1999, 09:37</td>
<td>Cirrus</td>
<td>10.8</td>
<td>9.2-12.0</td>
</tr>
</tbody>
</table>
coordinates, were imported into the systems. Two versions were calculated for each system, one with the original images and a second version with Wallis filtered images. As would be expected, the preprocessed version performed better for all systems. To obtain a quantitative evaluation of the matching quality of the systems, the computed DSM was compared with about 60 semi-manually measured points within the overlapping region of the two images of the 08 October 1999. For these images, with a mean cloud height of 4000 m (which gives an image scale of 1:190,000), the expected z accuracy according to Equation 2 is about 8 m. In the following, the results from the three systems are described in more detail.

Match-T

Match-T first extracts points with the Förstner operator in all images and then tries to match them. The results were not satisfying at all; in particular, the system found match points everywhere in the images, even in calm sky regions. Probably, the Match-T system assumes that in all parts of the image, good texture should be present, which is normally the case for land applications, and the Förstner parameters (which are not accessible to the user of the system) are then adjusted accordingly. The resulting DSM showed most problems to be at the cloud borders where the contours did not fall abruptly enough as in the outputs of the other two commercial systems. Due to the above problems, the results of Match-T were not further analyzed.

VirtuoZo

VirtuoZo uses cross-correlation and matches points defined in a regular grid of the template image with various strategies, depending on the terrain topography. VirtuoZo was used with the undulating matching strategy: with a 15- by 15-pixel patch dimension and match grid spacing. Ten-thousand seven-hundred points with an average spacing of 30 m were matched automatically, resulting in a height range of 3720 to 4380 m. Unfortunately, VirtuoZo cannot handle more than one camera. In our case with two different cameras and lenses (which have significantly different focal lengths, principal point coordinates, and radial and decentering distortion), this resulted in an average height error of about 100 meters, and a maximum height error of up to 300 meters compared with the manual measurements. Ignoring these absolute errors due to the wrong orientation, the relative heights were realistic, especially for the second version derived from the preprocessed images.

DPW 770

DPW 770 uses cross-correlation of match points defined in a regular object grid with two major methods (adaptive and non-adaptive automatic terrain generation) and various matching strategies. DPW 770 showed good matching results. As an optimal matching strategy, the adaptive method was chosen, with six pyramid levels and a patch size of 9 by 9 pixels, resulting in 88,000 points with an average spacing of 10 m. Table 4 shows the quality control of the results with the manually measured points. Because the DPW 770 system correctly imported both camera orientations, the remaining differences are caused by matching differences/blunders, by the interpolation of the grid (to compare with the manual points), and by the limited measurement accuracy of the manual points because of the poorly defined structure of the clouds.

**Derivation of Reference Data from Matching and Quality Analysis of Matching Methods**

For validation of the matching results of all systems, the data mentioned in next section were augmented by semi-automatic manual measurements of the cloud images. Points with good texture were selected in the template image, good approximations for the position of the corresponding feature in the other image were given manually, and then MPGC was used to refine the results. Points that were poorly matched were found through visual control and were excluded. It was estimated that the parallax errors of these points did not exceed one pixel. With this method, many discrepancies, primarily concerning the entire image format, and with better accuracy than that of the validation data. Although optimally, reference data should be an order of magnitude more accurate than the measurements tested, such accuracy is very difficult if not impossible to achieve, especially for points covering the entire image format. Furthermore, taking into account the accuracy requirements for CBH within Cloudmap, the accuracy of this reference data fully suffices. A problem is the quantification of blunders where reference data do not exist, e.g., in regions with poor texture. Such errors can be evaluated qualitatively by overlaying the matched points or derived contours on the stereo model using a digital photogrammetric station. It should be noted that such reference data from matching can be used for checking the image measurement accuracy of the matching algorithms only. Errors in the sensor orientation would go undetected because they influence both this reference data and the matching results. Thus, to estimate the absolute accuracy, the errors due to the orientation have to be added to the part due to image measurement errors. In these tests, due to the instability of the Kodak sensor, orientation errors did occur. With a stable camera, interior orientation errors have an insignificant effect compared to the image measurement errors, e.g., principal point coordinates can be determined to micrometer level. The sensor position as determined with GPS is in the cm level, and again is insignificant. The rotation angles as determined by the star calibration have an accuracy of 40 arc seconds which leads to an error of ±3 m (φ) and ±0.6 m (κ) at 4 km, and an error of ±22 m (ω) and ±2.5 m (κ) at 10 km (calculated by forward intersection of cloud points at different heights with ω, φ, and κ varied by ±40°).

**The Problem of Smoothed Discontinuities**

Area-based algorithms use a small area to estimate the parallax. When such areas fall across surface discontinuities, the result is a smooth average surface. Thus, discontinuous surfaces may be merged, while the propagation of these smooth (and inaccurate results) through the image pyramid often leads to chain reactions and incorrect approximations at object surface boundaries. Furthermore, if, for example, one of the two discontinuous surfaces has little or no texture, it is strongly pulled towards the surface with texture. Similarly, small textureless gaps between other object surfaces with texture are pulled towards these surfaces. These problems are even more critical in the given application of cloud matching, because clouds can have very strong discontinuities or even be multilayered, unlike the terrain. The same problems have been observed when matching clouds from spaceborne sensors within the Cloudmap project. All the above matching techniques are area-based and suffer from this problem, except for Match-T which,
however, showed other weaknesses, especially in the point selection. To avoid or at least reduce this problem, matching of point or edge features could be used. Point features are less unique than edges, and are less stable, especially with clouds. Thus, we tested an edge-based matching algorithm on the 08 October 1999 images that was developed at the IGP (Zhong and Balsavias, 2000). The method first extracts edges from both the template and patch image(s) with the Canny operator (Canny, 1986); the results are then converted into straight lines using least-squares fitting. Matching is performed using geometric constraints and rich edge attributes, including radiometric and color information in the flanking regions of each edge, in order 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. The extracted lines in the two cloud images are quite similar, which means that matching has a high probability of success (Figure 9). Their number is small (which makes matching easier and faster) but still sufficient for CBR determination. The matched edges are shown as thick lines in Figure 9. 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.

Validation of the Results with Coincident MAP Measurements
A special composite observing system for the MAP-SOP was set up in the region of the Rhine Valley (MAP Implementation Plan, 1999) (Figure 2). Most of the systems were operated more or less continuously during the whole SOP; some were switched on only during IOPs (Intensive Observation Periods of 1 to 5 days).

Visual Observations
Visual observations of current weather, including estimation of cloud parameters (cloud amount, cloud depth, cloud type, cloud-base height), were performed at half-hour intervals at the airport stations, at three-hour intervals at the main automatic climate stations, at four-hour intervals at the aero stations, and at six-hour intervals at all other climate stations of Meteo Swiss. It is important to note that these observations were sometimes done by different persons at the same station so that the subjectivity of the estimated values was not only between stations but also within the time series of one station. Data from the automatic stations Chur and Vaduz, the climate station Bad Ragaz, and the aero station Weesen were chosen for the 08 October 1999 10:58 and 13 October 1999 10:16 cases. On 08 October 1999, all stations reported cloud amounts between 1/8 and 3/8; the cloud type and height at Chur was cirrus with an estimated height of 5.1 to 7.0 km; at Weesen, altocumulus with a height of about 3 km above ground was observed. At 08:00, altocumulus with an approximate height of 4.5 km was reported at Chur. These observations were consistent with our images and results of altocumulus with a height range between 3.4 and 3.7 km. On 13 October 1999, Weesen and Vaduz reported fog; the cloud amount at Bad Ragaz and Chur was between 1/8 and 6/8 (06:00–12:00) and was of the cirrus type with a height range between 7.2 and 9.0 km. This case does fit with the lower clouds in our images but not with the higher layer. The estimation of cirrus cloud-base heights from ground-based visual observations is nearly impossible and the height is underestimated in most cases.

Lidar
A comparison was done with the data of the Pseudo-Random Noise modulation, continuous wave (PRN-CW) total backscatter lidar of the Observatoire de Neuchâtel (Matthey et al., 1996) located at Trübbach. This prototype lidar was in operation mainly during MAP-IOPs. The lidar signal of the 20 October 1999 case was unfortunately very weak due to the large height of the clouds; varying peak signals at 10.2, 10.7, 10.8, 11.0, 11.1, and 11.4 km above ground were found between 09:00 and 09:45 (Max Froid, personal communication).

A second comparison for the 20 October 1999 case was done with the Wind Lidar (TWL) from LMD, France, located at Vilters (Philippe Drobinsky, personal communication). Figure 10 shows the reflection layer of the cirrus clouds at an altitude between 9.0 and 11.0 km above ground. Unfortunately, the time difference between our measurements was already about 30 minutes and the horizontal distance between the lidar and camera stations was about 20 km. Nevertheless, a general correspondance between the imager and lidar values can be reported here as well.

Radiosondes
Seven temporary radiosonde stations were operated by the Swiss Army during the MAP-SOP in the greater Rhine Valley
area. They consisted of low-level sondes measuring temperature and wind, as well as high-level sondes measuring pressure, temperature, humidity, and wind.

A method for estimating cloud-base heights from radiosonde data is described in Chernykh and Eskridge (1996). In the sounding launched on 08 October 1999 at 11:00 UTC at Diepoldsau (Figure 11), the lowest cloud layer was well defined from about 630 to 600 hPa, which corresponded to a height of 3.9 to 4.4 km above sea-level. The temperature profiles of the low-level stations Heiligkreuz and Buchs showed the same shape. The results from the ground-based stereo images corresponded therefore very well with the lowest cloud layer values from these soundings.

**ATSR2 CTH (for Vertically Thin Clouds)**

Cloud-top heights from ATSR2 satellite images were calculated for 13 October 1999 10:18 as described in Poli et al. (2000). The field of view of the ground-based imager corresponds to only about 14 by 9 ATSR2 pixels. The retrieved mean height in this area was 12.0 km above sea level from the 11-µm channel, with an accuracy of ±500 m, which fits well to the heights estimated by the ground-based images. This case shows the possibility of coincident ground- and satellite-based stereo analysis of clouds and of the validation of satellite-based cloud-top heights of vertically thin clouds with ground-based imagers.

**Conclusions**

The measurements with the developed ground-based cloud imager during the MAP-SOP have shown the capacity of this photogrammetric system to automatically determine cloud-base heights. An important aspect for the choice of a sensor and camera is the possibility for accurate measurement and sensor orientation. The method to estimate the orientation parameters, with star calibration for the angles, GPS measurement of the camera positions, and the test-field calibration for the interior orientation parameters seems to be a realistic and also operationally usable method. The potential of the airplane calibration could be used for control of the consistency of the various orientation parameters. The problems of the Kodak DCS460 camera showed that an appropriate sensor should at least have a geometrically stable chip and allow longer exposure times which do not have to be taken manually.

Our own cloud-adapted matching algorithm already improved the accuracy of the successfully matched points compared with the commercial matching methods. Nevertheless, further constraints will be introduced in the future, especially for thin cloud situations or clouds with very little texture. First, spatio-temporal constraints from time sequences will be applied. Second, more than two cameras will be used to expand the number of points which can be used in the matching and to stabilize the matching in the self-similar texture of clouds. Next to these additional constraints, the derivation of the approximations and the quality control procedure will be refined and some cloud segmentation algorithms will be implemented.

The comparison of our CBH results from the MAP campaign with CBH data from other meteorological instruments and observations has shown a good correspondence. But because none of these alternative methods can measure the cloud height at an accuracy similar to the photogrammetric system, these data only give a rough comparison. Therefore, the next measurements within Cloudmap2 will be done at Zurich Airport, next to four Vaisala 25K ceilometers, which will give us further knowledge about the absolute accuracy of our system.

**Acknowledgments**

The MAP data were provided by Christian Häberli (radiosonde), Philippe Drobinski [LMD Idar], Max Frioud [lidar, NE], and the Swiss Meteorological Institute. We thank Merc Cocard, ETHGGL, for the GPS software and support, the Astronomical Institute Berne for the star processing, the Swiss Army for the calibration flights, Kodak and FHBB Muttenz for providing the DCS460 cameras, and Chunsun Zhang for the edge matching software tests. This work is funded by the Bundesamt für Bildung und Wissenschaft (BBW) within the EU-project CLOUDMAP (BBW Nr. 97.0370).

**References**


(Received 26 July 2001; revised 11 October 2001; revised and accepted 06 March 2002)