GROUND-BASED CLOUD IMAGES AND SKY RADIANCES IN THE VISIBLE AND NEAR INFRARED REGION FROM WHOLE SKY IMAGER MEASUREMENTS

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ABSTRACT

Automatic cloud documentation from the ground is one of the basic tools to set up cloud climatologies with high resolution in space and time. Ground-based cloud data are of specific importance to study the role of clouds on the radiation balance of the earth's surface and the lower atmosphere. They can also provide ground-truth information for satellite-retrieved cloud parameters.

A new version of the Whole Sky Imager (WSI) was designed and developed at the University of California, San Diego (UCSD) for Deutscher Wetterdienst (DWD), and installed at the Meteorological Observatory Potsdam of DWD in December 1999. The new WSI design will be discussed, and first results of measurements be presented.

1. Introduction

Clouds are a unique phenomenon of the atmosphere. As soon as they build from water vapor, absorption of heat radiation by water vapor, which is the major atmospheric greenhouse gas, is complemented by scattering of short-wave solar radiation and emission/absorption of liquid and/or solid water particles. The additional scattering and absorption due to clouds changes the atmospheric heating rates as well as the amount of solar radiation including biologically effective UV radiation reaching the earth's surface. Clouds are not only a part of the hydrological cycle, but they also provide a medium for heterogeneous chemical reactions of trace gases in the formation of secondary aerosols, both of which affect transfer of solar and terrestrial radiation.

Ground-based cloud observations have been mainly performed by visual observations at weather stations. Satellite-based cloud images have added valuable information to global cloud data bases particularly over the oceans, where ground-based observations are sparse. Though visual observations have provided basic information for weather analysis and climate studies, their use is restricted to limited resolution in time and prone to observer errors.
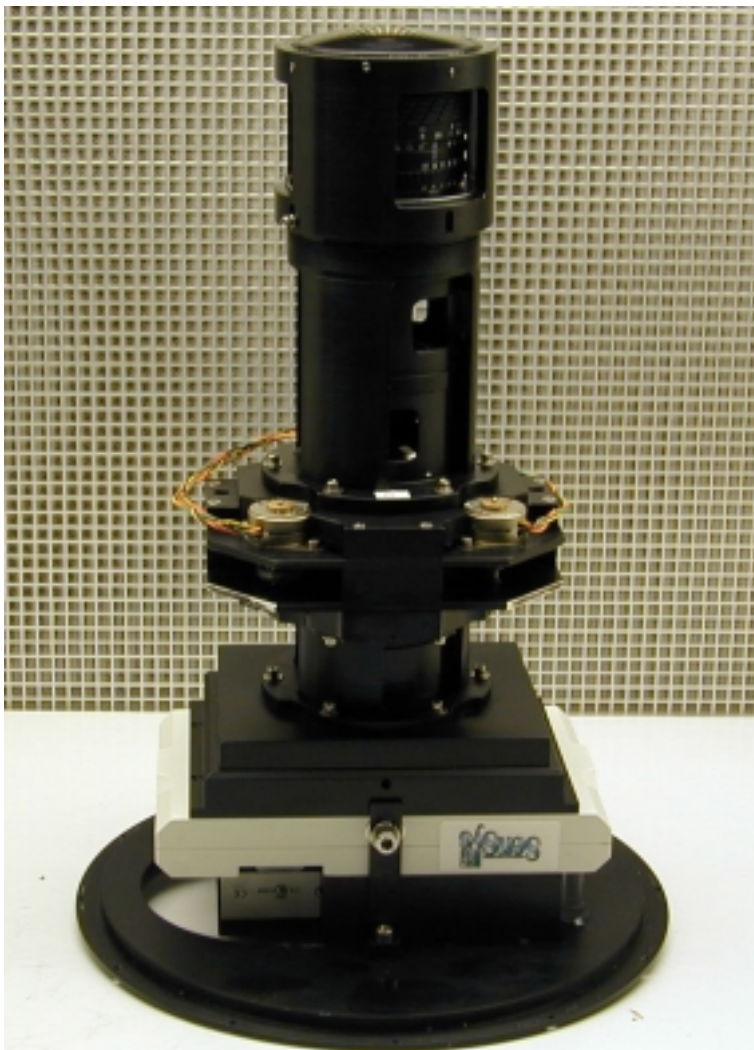
Automatic ground-based sky imaging such as that with the Whole Sky Imager (WSI) provides cloud data with high resolution in space and time and is thus capable of adding valuable information to the existing ground-based and satellite-based data bases. Different versions of WSIs developed at the University of California San Diego (UCSD) have been used for nearly two decades at different sites including more recently the three stations of the Atmospheric Radiation Monitoring (ARM) Program. A new type of Daylight WSI that acquires digital images of the whole sky (180° field of view) in channels of the visible and near infrared

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region was developed at UCSD upon requests of the German Weather Service (DWD). This Day WSI was designed to obtain high quality imagery appropriate not only for cloud assessment, but for determination of absolute radiance distribution. It was installed at the DWD Meteorological Observatory Potsdam (52° 22' E, 13° 5' E, 107 m asl) in December 1999 and has been working reliably with one interruption to correct alignment of the filter wheels. Some general features of the new WSI design will be discussed and first results of measurements will be presented including preliminary comparisons with model calculations and cloud cover data both from another type of sky imager as well as from standard visual cloud observations.

2. Instrument design

The new WSI is based on the experience gained at UCSD with the development of other types of Whole Sky Imagers (Shields and Johnson 1989, Shields 1998, Shields, 2000). The new Daylight Visible/NIR WSI, designated WSI VIS/NIR 7 in this paper, while similar in concept to the earlier imagers, includes several new hardware and software features. The optical design consists of a digital CCD (charged coupled device) camera Sensys KAF 1600 with a 1536 x 1024 pixel array manufactured by Photometrics. Its CCD pixel size is 9 μm x 9 μm, and its dynamic range is 12 bits. There are three gains corresponding to factors of 0.5 x, 1 x, and 4 x amplification. It is cooled to 10° C to reduce dark current, and has a readout noise of less than 1 count in 0.5 x and 1x gain, and 2 counts in 4 x gain. Light enters the WSI through a Sigma 8 mm f4 fisheye lens with a 180° (2π) field of view. It is protected by an acrylic dome of about 85 mm diameter. An optical lens relay consisting of 10 lenses bundles the light such that the incidence angles of the light are reduced to under 5 degrees, when it enters the filter surface. Two motor-driven filter wheels with 4 holes each hold 6 circular filters with a diameter of 25.4 mm (one hole in each wheel is left open). The overall transmittance of the optical system was so good that a 2 log neutral density filter was included in the light path to reduce the incoming light by 2 orders of magnitude for all filter positions. The camera itself with its foreoptics can be seen in Figure 1. The camera housing is hermitically sealed and purged with nitrogen to prevent condensation of water that could affect the optics. It is embedded in an environmental housing made of a double-plate aluminum with foam plastics in between to keep heat exchange between the inner part of the housing and the environment small (Fig. 2). The temperature in the environmental housing is kept constant at a temperature of 20° C by an air conditioner of 1500/1800 BTU including a 500 W heater.

Fig. 1 WSI VIS/NIR 7 camera, two motor-driven filter wheels, the lens system with spacers and with the fisheye lens on top

The sun is occluded by a motor-driven equatorial-mounted circular occultor to shield the dome and optics from stray light which would otherwise distort the radiance field, and prevent CCD blooming. As the occultor holds a 4 log neutral density filter, the sun can be seen in the image as a small spot to allow for manual occultor adjustment. Six occultor arms of different lengths are exchanged periodically to adjust for seasonally changing solar declination. The occultor as well as the camera functions are controlled by an Accessory Control Panel (ACP), which is connected to the camera unit and the computer. The ACP also allows one to manually move the occultor and the two filter wheels to selected positions.

The WSI software developed by UCSD runs under the camera software V++ from Roper Scientific in the Windows NT environment. Special V++ routines including C routines perform all the steps to acquire images, perform corrections, determine cloud decision images and cloud statistics as well as calibrate the images. Exact time is provided by a GPS (Global Positioning System) clock board installed in the PC with an antenna on the roof top platform of the measuring site. This platform provides an unobstructed horizon for sky radiance and solar irradiance measurements to at least 4° elevation angle.

Fig. 2 Whole Sky Imager VIS/NIR 7 at the Central Radiation Station of the Meteorological Observatory Potsdam

3. Radiometric Calibrations

The WSI was carefully calibrated at UCSD, in order to characterize system performance and provide absolute radiance distributions from the imagery. Those which characterize performance are not specifically reported here. The calibrations which are applied to the imagery are as follows:

- correction for dark current
- flat field correction
- correction for signal non-linearities
- rolloff correction.
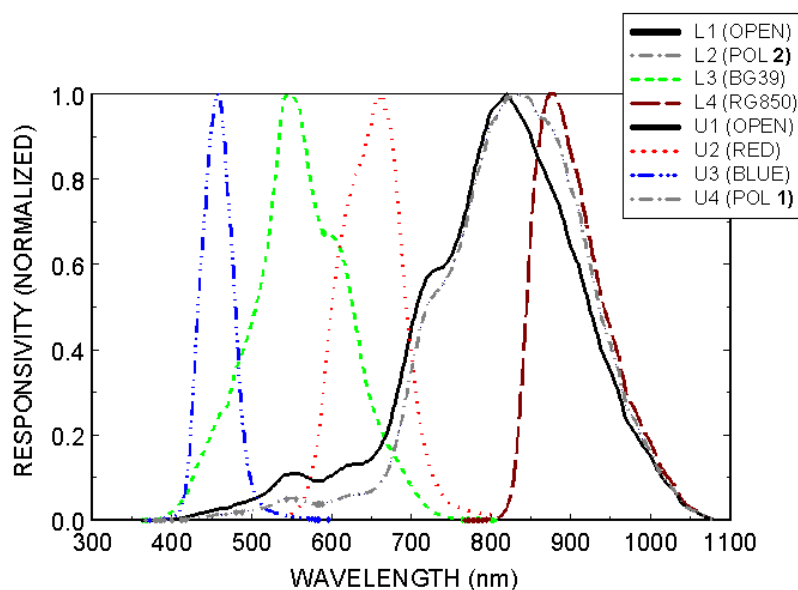- spectral responsivity
- absolute radiance calibration

Dark current, is a measure of the electronic bias created by the electronics, and the thermally generated dark current of the CCD. As the camera is kept at a constant temperature of 10° C, the WSI dark current depends on exposure time and gain only. It is determined by taking a measurement with the shutter closed and with

the exposure time and gain of the sky image close in time to the sky image acquired afterwards. The dark image is subtracted (pixel by pixel) from the raw sky image immediately after the sky image is acquired, and the dark-corrected image is stored. Dark current correction may not be valid, if pixels become saturated by dark current with high gain and with very long exposure times (>> 10 s). However, the system is sensitive enough to keep the exposure time much lower than 10 s except with thick clouds close to sunset and sunrise.

A *flat field correction* of CCDs is normally needed to account for differences in effective gain of each pixel or for systematic differences in the charge transfer efficiency. Flat files for WSI VIS/NIR 7 were measured by acquiring images with a 1-meter integrating sphere in the laboratory. Their application to test images revealed that the variances of brightness within Regions of Interest (ROI) were not significantly reduced by the flat field correction. This means that the quality of the CCD and the optical system is so good that a flat field correction is not needed to be applied to WSI VIS/NIR 7 field data.

Non-linearities of the sensor used in this Day WSI system consist of two parts: a non-linearity between signal and radiance, and an apparent non-linearity that results from an offset $E_0 = 10$ ms in the shutter opening time. The measured non-linearities are used in the correction of non-linearities as a look-up table. Non-linearíties were determined by acquiring images of a standard Lambertian plaque homogeneously reflecting light of a 1000 W FEL type halogen lamp at varying distances. After applying the correction for non-linearities to the images, the remaining uncertainty due to non-linearity was found to be less than 0.2 %.

Rolloff means the change in sensitivity of pixels as a function of incidence angle. It is determined by measuring signals of the illuminated plaque at incidence angles varying between 0° and 90°. A rolloff correction factor for the visible channels and another one for the near infrared channel are applied to sky images in dependence of incidence angle to correct brightness values of pixels.

Spectral responsivity of the WSI system is mainly determined by the broad-band filters and the camera responsivity, and is modified by the neutral density filters. Nominal spectral transmittances of all the filters were measured by an OL750 as well as an OL754 Optronics spectradiometer at Potsdam. The measured nominal transmissions of the filters were multiplied with the spectral transmissions of the ND filters and the spectral responsivity of the camera as provided by the manufacturer to give the spectral responsivities of the WSI in the different filter channels. It can be seen in Fig. 4 and in Table 1 that in addition to the two standard filters "BLUE" and "RED" used in earlier WSI versions, sky radiances can be obtained in other regions over the visible into part of the near infrared spectral region to wavelengths up to almost 1100 nm. Due to the shape of the camera responsivity and the spectral transmission characteristics of ND filters, spectral responsivities of the WSI system are shifted to longer wavelengths as compared to the nominal spectral transmission of the broad-band filters.

Fig. 4 Spectral responsivity of the WSI VIS/NIR 7. Spectral channels are designated by L1, ... L4 for the lower, and U1, ... U4 for the upper filter wheel.

Table 1 Nominal transmission and camera responsivity parameters (peak wavelength, wavelengths of 1 %, 50 % transmission and full bandwidth at half maximum), and effective (including neutral density filters and camera responsivity) spectral responsivity of the WSI VIS/NIR 7 spectral channels. L1, ... L4 and U1, ..., U4 refer to the lower and upper filter wheel, respectively.

	CAMERA	OPEN (U1, L1)	RED (U2)	BLUE (U3)	POL (U4, L2)	BG39 (L3)	RG850 (L4)
NOMINAL							
PEAK	810	----	646	450	1100	517	1096
1 %	379, 1065	----	548, 750	382, 492	312, ---	313, 711	816, ---
50 %	529, 921	----	411, 498	424, 474	787, ---	339, 617	851, ---
FBHM	392	----	87	50	---	278	---
EFFECTIVE							
PEAK	----	820	664	458	840	550	878
1 %	----	426, 1067	550, 800	406, 544	452, 1067	395, 739	814, 1068
50 %	----	707, 923	601, 694	434, 480	720, 936	506, 627	845, 942
FBHM	----	216	93	46	216	121	97

The *absolute calibration* of the WSI VIS/NIR 7 was performed at the Marine Physical Laboratory of UCSD using a plaque of known spectral reflectance ($\approx$ 0.99) illuminated by a 1000 W FEL lamp. Three different lamps were used: two DWD lamps (OM013 and SL-129) that are traceable to the German Physikalisch-Technische Bundesanstalt (PTB) at Braunschweig, and one UCSD lamp (S80C) that is traceable to the US National Institute of Standards and Technology (NIST). The calibration constants C (W^{-1} m^2 µm sr) were determined for each gain and each filter set at an incidence angle of 0 degrees (normal incidence) such that it corresponds to a radiance that creates a signal of 1000 at an exposure of 100 ms

$$C = N \cdot \frac{1000}{S'} \cdot \frac{E + E_0}{100 + E_0}$$

with
S': signal corrected for dark current and for non-linearity as a function of gain (1, 2, 3), and normalized to S' = S, when S=1000
E: exposure time (ms)
E_0: offset in effective exposure time (10 ms)
N: radiance (W m^{-2} $µm^{-1}$ sr^{-1}).

Calibration constants (W^{-1} m^2 µm sr) are applied to dark-corrected raw images to derive absolute radiances. Based on the absolute uncertainties of the three calibration lamps, which differed by no more than 2 %, and the consistency of the calibration results, the uncertainty of the calibration constants of the WSI VIS/NIR 7 was estimated to be between 2 and 4 %.

4. Angular Calibration

The angular calibration is designed to determine the relation between the angles (zenith and azimuth) in objects space and the pixels in image space. Angles with respect to a point marked by a plumb bob were determined with a precision transit, and indicated on laboratory walls. The WSI is then aligned with this same point, and an image of the room acquired. Given the radius r from the image center (x_0, y_0), zenith angles Θ are given by

$$\Theta = \frac{-a_1 + \sqrt{a_1^2 + 4 \cdot a_2 \cdot \dfrac{r}{R_0}}}{2 \cdot a_2}$$

with $R_0 = 477$, $a_1 = 0.0149102$, $a_2 = -4.00180 \cdot 10^{-5}$. The azimuth Φ counted clockwise from North is given by

$$\Phi = \arctan(\frac{x - x_0}{y - y_0})$$

Image resolution in degrees per pixel can be expressed by zenith angle change per radius change

$$\frac{d\Theta}{dr} = \frac{1}{R_0 \cdot \sqrt{a_1^2 + 4 \cdot a_2 \cdot \dfrac{r}{R_0}}}$$

WSI VIS/NIR 7

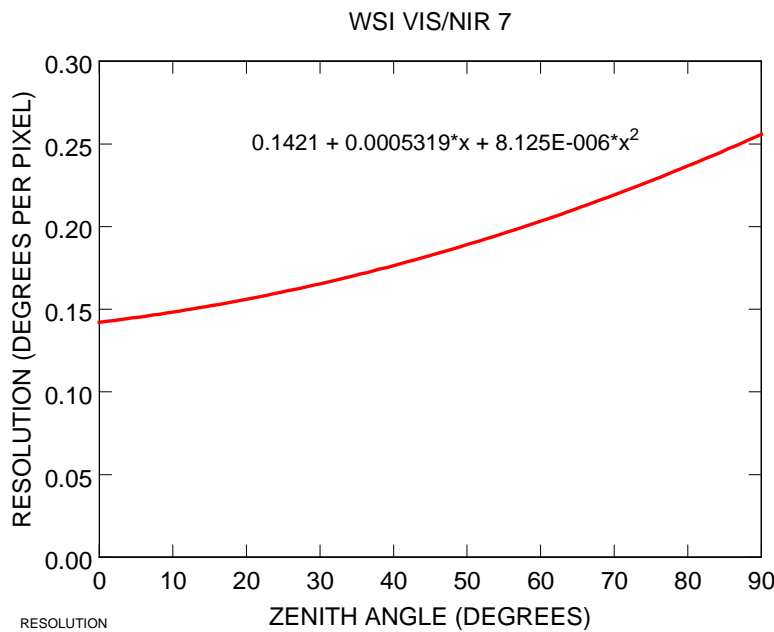$0.1421 + 0.0005319*x + 8.125E\text{-}006*x^2$

Fig. 3 shows that the resolution of WSI VIS/NIR 7 is between 0.14 degrees per pixel in the image center and 0.26 degrees per pixel near the image margin.

Fig. 3 Image resolution of the WSI VIS/NIR 7 as a function of zenith angle

The solid angle Ω is used in computations of the spectral irradiance. The change of solid angle per pixel value can be determined from the relation

$$\frac{d\Omega}{dA} = \frac{\sin\Theta}{\Theta} \cdot \frac{1}{R_0^2 \cdot (a_1 + a_2 \cdot \Theta) \cdot (a_1 + 2 \cdot a_2 \cdot \Theta)} \cdot \frac{\pi}{180}$$

5. Measurements and cloud decision

It turned out during the development of the WSI VIS/NIR 7 that the software to process raw images for determining cloud decision images, average cloud cover and cloud pixel statistics of the upper hemisphere and in selected regions of interest, and the software to calibrate raw images into radiance files might interfere with the software that acquires raw images and stores them. Therefore, processing of raw images is performed either at night on the PC driving the software to acquire images or on another computer at any time. Due to the amount of data to be stored (1.8 Mbytes for one spectral 16 bits image of 12 bit data, 7.5 Mbytes for one floating point radiance image), the routine schedule was restricted to a sequence of 7 spectral images taken at time steps of 10 minutes from sunrise to sun set. An amount of more than 400 GBytes of measured raw images has been stored between December 1999 and November 2000. Improvements in the reliability of the software including V++ are still needed, because the V++ driving software occasionally stops acquiring images for unknown reasons from time to time with error messages such as memory problems or data storage errors.

The cloud processing algorithm is limited currently to optically thick clouds. It uses the ratios between blue and red image that are acquired close together in time, thresholds the resulting image and creates a stored cloud decision image. An additional false color image is created for visual assessment. An example of a false color cloud decision image determined from the red and blue images grabbed on November 9, 2000 at 14.28 UTC is shown in Fig. 5. While pixels classified as cloudy appear white or yellow, the rest of the image showing blue color is either cloudless portions of the sky or thin clouds. A thin cloud algorithm is being developed at the UCSD and will be added to the processing software of the WSI VIS/NIR 7 in spring 2001. Total cloud fraction of thick clouds counted from pixels classified as cloudy for the particular case was 0.68 (68 %).

Another instrument for ground-based daylight cloud imaging on loan from Aero Laser in Munich (Haaks, private communication, 2000) was available for preliminary cloud cover comparisons at Potsdam from October 23 to November 14, 2000. This Total Sky Imager (TSI-440), which is manufactured by Yankee Environmental Systems (YES 2000) uses a 3 x 8 bits color camera with a 352 x 288 pixel array. The camera looks down at a slowly rotating spherical mirror that has a black strip to occlude direct solar irradiance from the camera (but does not shade the mirror). An example of the TSI raw color image and the cloud decision image derived from the color image on the same date and time is shown in Fig. 6. Cloud fraction determined by the TSI algorithm for this case is 0.40 for thick clouds and 0.11 for thin clouds.

It was decided to increase the sampling rate of the WSI to 2 minutes for the comparison campaign to enable a better analysis of the cloud data determined from both instruments. It should be mentioned that the threshold values in the cloud decision algorithms of both instruments can be changed to give the least error of cloud fraction, though this is not an easy task due to the lack of cloud cover data that are close to reality. As an example, Figure 7 shows an example of the results of cloud fraction data derived from both WSI and TSI measurements at two minute time steps compared to hourly visual cloud observations performed at the Potsdam weather station according to WMO guidelines. The excellent time resolution of the automatic sky imagers can not be reached by visual observations, but the general pattern of diurnal changes in cloud cover is reflected by the visual observations. Both WSI and TSI show similar short-time variations, with some systematic lower cloud fractions observed by the TSI compared to the WSI in particular at low solar zenith angles (cloud cover from TSI is derived for solar elevation angles of greater than 3° only, while WSI data go down to solar elevation of 0°).

Fig. 5 Cloud decision false color image derived from the red and blue images of the WSI VIS/NIR 7 on November 9, 2000 at 14.28 UTC at Potsdam. South is at the bottom and East at the right-hand side. White and yellow areas designate thick clouds, while blue areas correspond to cloudless sky or thin clouds. Total thick cloud fraction was 0.68. A strip-like pattern due to a contrail can be seen stretching along the zonal direction. Visual cloud observations gave 2 to 4 Octa Sc, 2 Octa Ac and 2 Octa Ci fib at 14 and 15 UTC, and short-lasting contrails (less than 14 minutes), which did not develop into Cirrus, between 8 and 14 UTC.
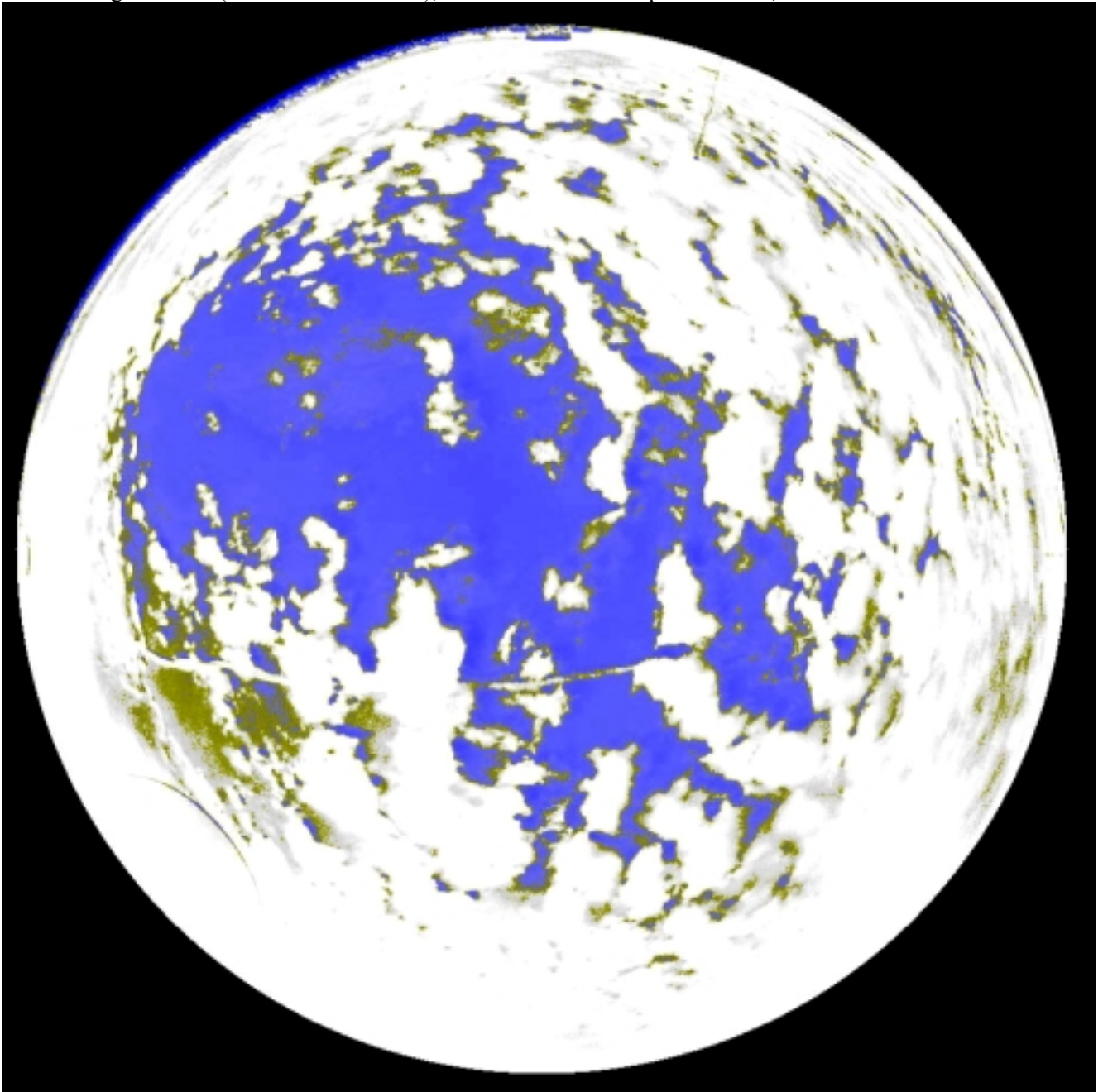
Fig. 6 Sky image taken with a Total Sky Imager (TSI) on November 9, 2000 at 14.28 UTC at Potsdam. The original color image is shown on the left-hand side and the cloud decision image on the right-hand side. South is at the bottom and east on the right-hand side. The strip extending from the image center to the upper rim of the spherical mirror is the support lever of the camera, which is in the image center
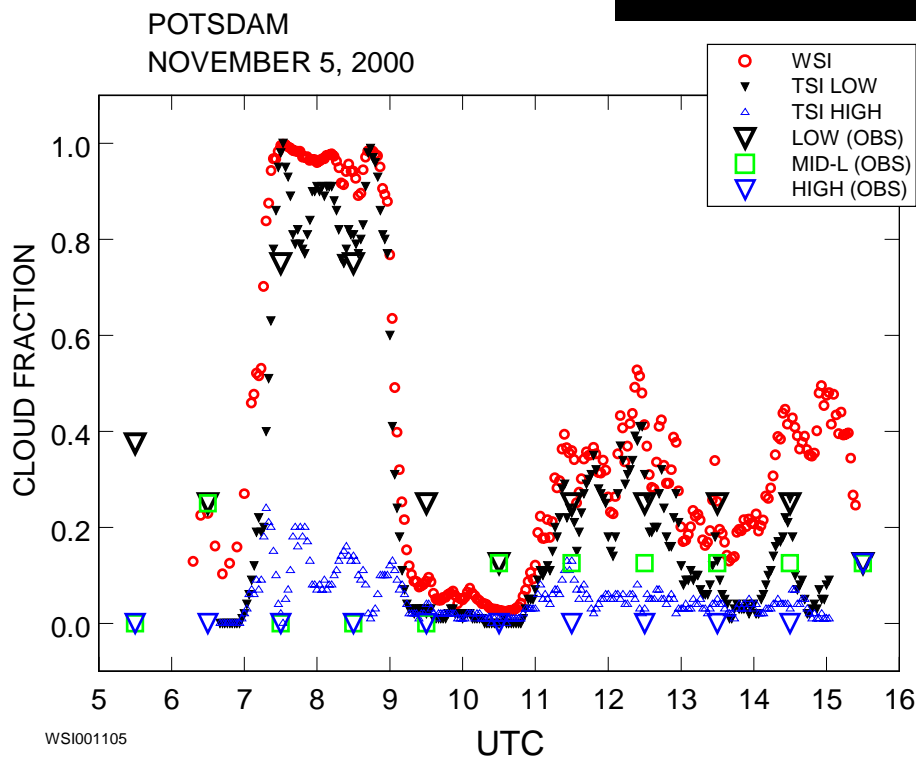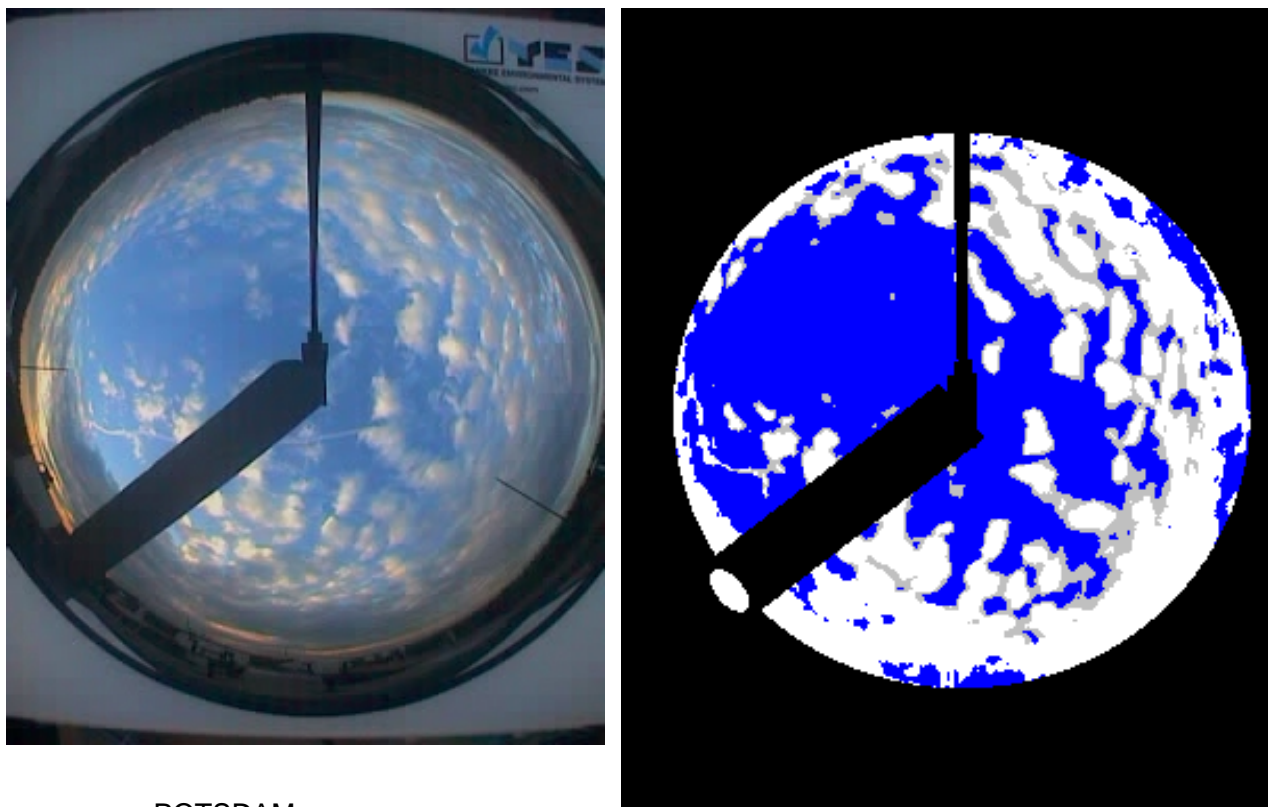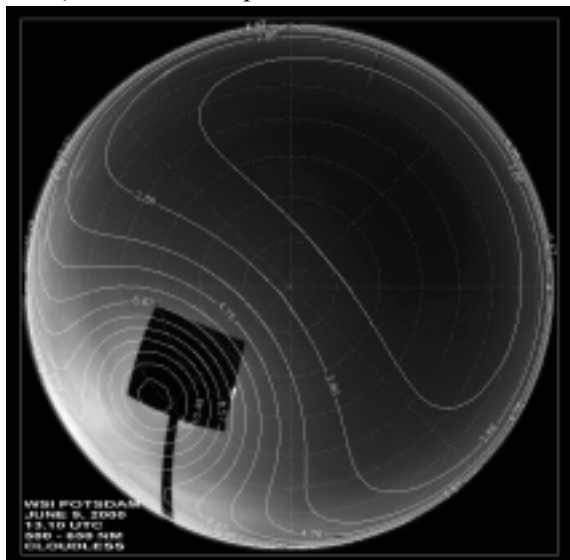

Fig. 7 Cloud fraction as determined from measurements with the Whole Sky Imager (WSI, thick clouds only), the Total Sky Imager (TSI, thick and thin clouds), and hourly visual observations of low, mid-level and high clouds made at the Potsdam weather station on November 5, 2000

6. Model calculations

Using a Discrete Ordinate Method Model a few radiance calculations have been carried out for the spectral region from 280 through 1100 nm in 15 bands (channels), for 19 zenith angles (0, 5, 10, ...90), and for 37 azimuth angles (0, 5, 10, ..., 180). The model assumes a plane-parallel surface, with refraction of radiation not accounted for, i.e. errors can be expected to occur with zenith angles greater than 70°. Absorption by H_2O, O_3 and O_2 are taken into account. Spectral albedo was taken from measured values (Feister and Grewe 1998). The aerosol parameterization in the model was scaled with optical thicknesses taken from spectral measurements at the site (Weller 2000) and total water vapor from microwave radiometer measurements (Güldner and Spänkuch 1999). Radiance calculations were made for a 5 x 5 degrees coarse grid and were extrapolated to a fine grid of 0.2 x 0.2 degrees. Column ozone was taken from measurements of a Dobson or Brewer spectrophotometer at the site (Spänkuch et al. 1999). An example of the results is shown in Fig. 8. The general pattern of diffuse radiance (isolines) reflects the brightness values in the measured image quite realistically that is shown as an overlay in Fig. 8, though a few problems still need to be solved with the projection and comparison of measured and calculated data. Model calculations will be continued.

Fig. 8 WSI VIS/NIR 7 image in the near infrared channel on June 9, 2000 at 13.10 UTC. Isolines refer to the model calculation carried out for cloudless sky.

7. Conclusions

The WSI VIS/NIR 7 provides information on cloud cover, cloud distribution and sky radiance in the visible and near infrared region with high resolution in space and time. WSI cloud cover data can be used for cloud studies and parameterization of cloud effects on radiation and climate. Their use will be valuable in deriving improved cloud flags to classify solar radiation data (Feister and Gericke 1998). In addition, they have the potential to be used as ground-truth for cloud data derived from satellite sensors. In combination with a second ground-based sensor, they may even provide more cloud parameters in addition to cloud cover and distribution, such as 3D cloud structures. Further tasks will include collection of more data, improvement of cloud algorithms, in particular for high clouds, and comparisons of the WSI with other instruments.

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