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4.7 AUTOMATED DAY/NIGHT WHOLE SKY IMAGERS FOR FIELD ASSESSMENT OF CLOUD COVER DISTRIBUTIONS AND RADIANCE DISTRIBUTIONS

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1. INTRODUCTION

In response to a continuing need for assessment of the characteristics of clouds and the sky, the Marine Physical Lab (MPL) at Scripps Institution of Oceanography has developed a series of digital Whole Sky Imagers (WSI) for sky and cloud assessment. These instruments are used for a variety of applications, including climate research and military applications. They are ground-based, acquiring images such as that shown in Figure 1. In Fig. 1, the center of the image is the zenith, and the edge of the image is the horizon.

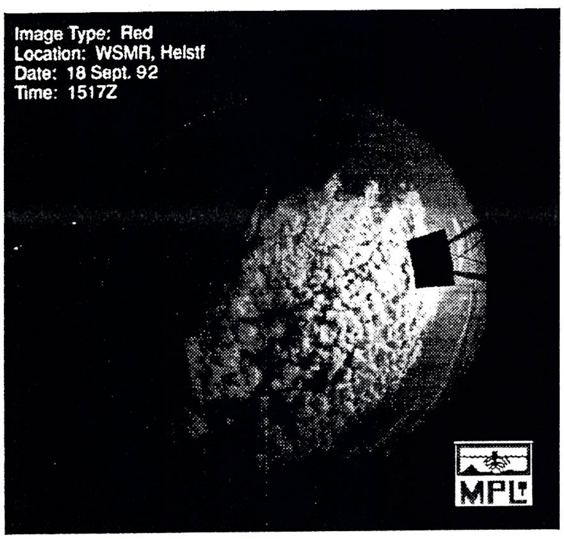

Figure 1

The WSI's are used for assessment of cloud cover, sky sector cover, cloud spatial and temporal characteristics such as cloud location and size, and calibrated radiance distributions for the sky and clouds. Current generation Whole Sky Imagers are capable of fully automated data acquisition from full daylight down to starlight. An image acquired under starlight is shown in Fig. 2.

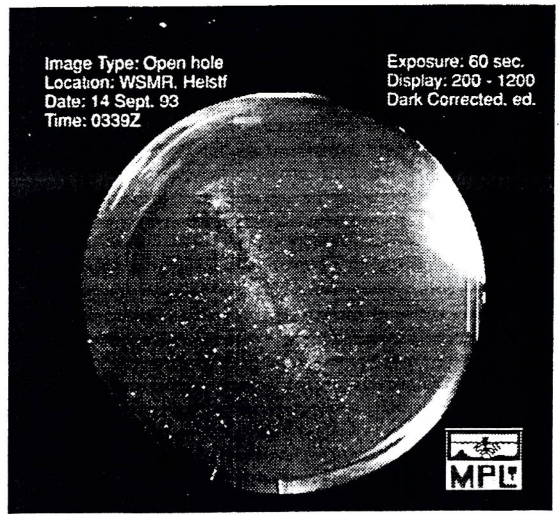

Figure 2

2. DEVELOPMENT OF THE MPL WHOLE SKY IMAGERS

The current generation of digital Day/Night Whole Sky Imagers were developed over many years by the Atmospheric Optics Group at SIO's Marine Physical Laboratory. The earliest WSI's used by our group consisted of a silvered dome with a remote-controlled 35 mm battery driven camera. These were used in the 1950's for assessment of the sky conditions during acquisition of ground-based sky radiance measurements with photometers. In the 1960's, the domes were replaced with lenses, for use looking both up and down on an instrumented aircraft. These analog images were used in conjunction with scanning photometers which acquired radiance distributions for the upper and lower hemisphere. Whereas the scanners were quantitatively quite accurate, they did not have the advantage of simultaneous data acquisition in all directions, as the current WSI's do.

In the 1980's, with the availability of digital imagers such as CCD's (charge coupled

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device) and CID's (charge injection device), the feasibility of combining the radiometric accuracy of a quantitative detector with the simultaneity of a fisheye view became practical. MPL fielded its first digital WSI's using CID's in the early 80's, followed by fielding of several fully automated WSI's at several sites, acquiring data once a minute over a two year period in the late 80's. These data were acquired in order to obtain a data archive large enough to provide statistically significant estimates of cloud free line of sight probabilities, as well as cloud free arc probabilities. The instruments operated autonomously, acquiring data under instrument control with occasional routine maintenance. The early development of these Day WSI's is documented in Johnson 1989.

The first cloud detection algorithm based on a red/blue radiance ratio was developed by MPL during the 1980's, and was used to evaluate the data base. These cloud algorithms (called cloud decision algorithms) provided automated analysis of the digital images, determining the presence or absence of clouds on a pixel-by-pixel basis. A 14-month set of data at several sites has been processed through the cloud algorithm, and are appropriate for use in Cloud free line of sight (CFLOS) studies. The algorithm, data processing, and sample CFLOS studies are documented in Johnson 1991.

In the early 1990's, a Day/Night WSI capable of data acquisition under 24-hour operation was developed. . The current version of the Day/Night WSI is shown in Figure 3. Even though capability below quarter moon lighting conditions was not promised to sponsors, the group was successful in developing a digital imager which is fully operational down to starlight conditions. Like the Day WSI, it is fully automated, adjusting itself to the ambient lighting conditions and acquiring and archiving data at user-selected intervals. This instrument was first fielded in 1992, and has been used for a variety of applications. For example, it is used to detect the presence of clouds, particularly at night, during tests related to tracking missions or turbulence experiments. More recently, other applications include monitoring of cloud cover and distribution for use in climate research. The first version of the Day/Night WSI is documented in Shields 1993a and b.

Since the Day/Night WSI's were developed, their capabilities have continued to increase. Current systems are capable of acquiring data in both the visible and near infra-red, and can be calibrated to provide radiance distributions for the full sky at 1/3 degree spatial resolution, both day and night. Further hardening of the sensor has been an area of emphasis for some sponsors, for application at remote sites or under inclement conditions. For other sponsors, refinement of capabilities has been an emphasis, with higher pointing accuracy and more interactive user control, as described in Shields 1997. The characteristics and design of the instrument will be described in more detail in the following section.

3. INSTRUMENT DESCRIPTION AND THEORY OF OPERATIONS

MPL's Whole Sky Imager uses a 180 degree fisheye lens in combination with a filter changer and a very sensitive low-noise CCD camera. We chose to use a fisheye lens, rather than a silvered dome, because our experience with silvered domes indicated that they have poor temporal stability, i.e. they tend to age, and they are very difficult to calibrate reliably, both in terms of the radiometric calibration and the geometric (angular) calibration. In order to acquire the full sky image, the optical image should be smaller than the CCD chip, so that the image will underfill the chip. In earlier systems we developed, the image size was reduced with an optical relay, which also stretched out the back focal length to allow inclusion of filter wheels. In the Day/Night WSI, these two requirements are accomplished using a fiber optic taper.

A filter changer was developed, which can hold up to eight filters. For the Day/Night WSI, one filter wheel holds spectral filters at 450 nm, 650 nm, 800 nm, and open hole, and the second filter wheel holds neutral density filters of 0 to 3 logs. The advantage of this approach is the ability to choose different filters for different applications, and a much higher accuracy in calibration. The filters at 450 nm and 650 nm were chosen after studies of our archived scanner data, and related modeling studies, as being the most appropriate for the cloud algorithm. We are just beginning to acquire the data with the 800 nm filter, which should enhance contrast between sky and thin clouds. The open hole is used under starlight. The neutral density filters are used to help

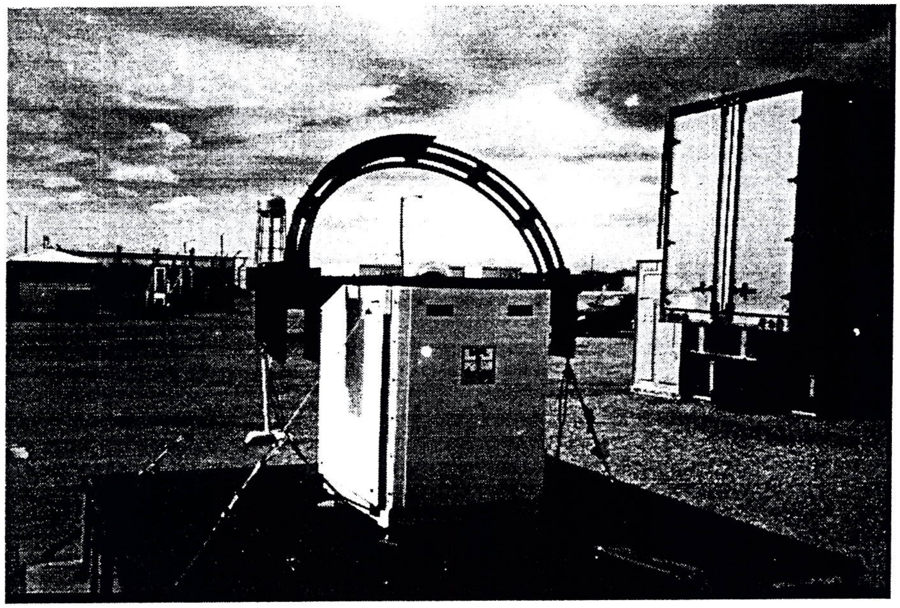


Figure 3 WSI Sensor System in its Environmental Housing

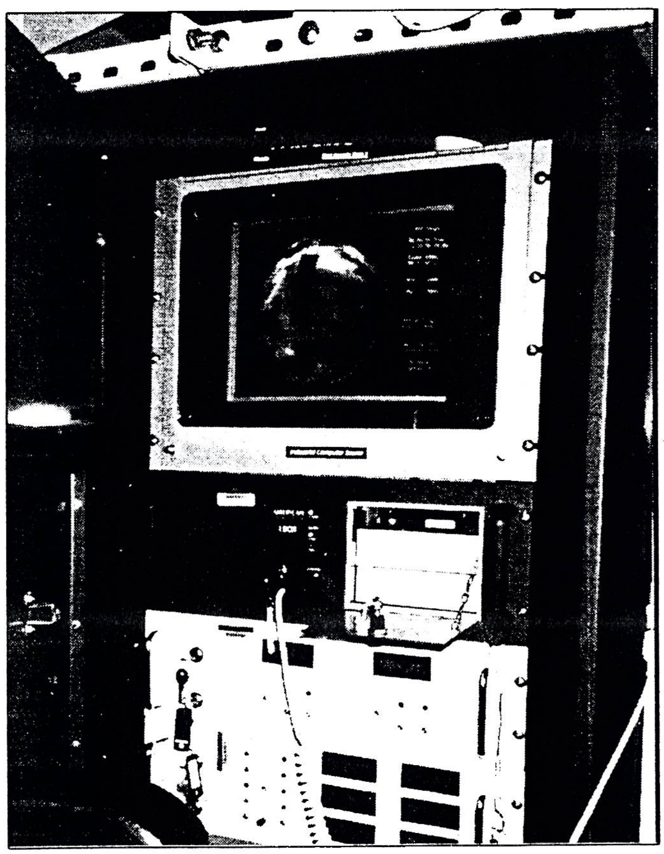


Figure 4 WSI Controller System

enable the shift from daytime to nighttime sensitivity.

The CCD camera is perhaps the most critical component in the basic optical package. We are using a Photometrics CCD camera, with 16-bit digitization and very low noise. With a readout noise of only 1 count out of 65,535 counts, the system has very high precision and large dynamic range. Longer exposures can be used at night to extend the dynamic range. The system is currently set up to yield a dynamic range of over 10 decades. (A larger range is possible, but not required for the current applications.) Even though the dark current noise becomes dominant over readout noise at night, the measurement noise is still significantly less than the Shot noise, i.e. the quantum variation in the light field.

The system is housed in a nitrogen-purged camera housing to protect the optics, and the camera housing and camera electronics are housed in an environmental housing appropriate for outdoor use, including climates such as the desert, tropics, and the arctic. The housing is thermally controlled, so that camera electronics are kept at a reasonably cool temperature, and several sensors in the housing provide feedback to the computer regarding the health of the system. The WSI is controlled by electronics packages built by MPL, which allow either manual control or automated control via a PC. The controller is shown in Fig. 4.

The data archival software include control of the sensor components such as the camera, filter changer, and solar/lunar occultor. The system is a "smart" system, i.e. it has many self checks based on monitored conditions such as system temperatures. Flux control algorithms developed at MPL are included in the acquisition software, for automated adjustment of the settings as light conditions change. Real-time versions of the cloud decision algorithms are applied automatically, if desired. The input file controls many options such as whether to apply the real time algorithm, and user-selected data acquisition intervals. The systems may be left fully autonomous, or may be changed interactively by the user. At one site, networking options allow a user at a remote site to change many of the operating parameters. For example, data can be acquired routinely at 10 minute intervals, and then an interactive user at a remote site can request that data be acquired 6 times per minute and sent immediately via network to the remote site for evaluation. The operational characteristics vary somewhat depending on the sponsor's applications and priorities.

4 CALIBRATED SKY RADIANCE

The calibrated sky radiance may be determined in the selected spectral bands (currently 450 nm, 650 nm, 800 nm, and open hole in most systems). That is, the signal measured in each pixel may be calibrated to provide the radiance in the direction corresponding to that pixel. The typical radiometric calibration measurements acquired for the Day/Night WSIs include the following. The calibrations are acquired with a NIST-traceable FEL standard calibration lamp and 3 m calibration bar.

Dark current: Originally calibrated in the lab, this measurement is repeated in the field. It characterizes the dark current in each pixel as a function of exposure.

Flat field: This calibration characterizes the difference in gain for each pixel. This is a function both of the CCD and of any non-uniformities in the fiber optic taper.

Linearity: Two types of system linearity are calibrated. The linearity of the CCD response as a function of signal level is measured, and the linearity of the system response as a function of exposure level is measured. This latter measurement is also used to determine the effective shutter opening time.

Uniformity and Precision: The statistical spatial variance on the chip is measured, to characterize the uniformity, and the statistical temporal variance is measured, to characterize the precision.

Filter Transmittance and Chip Responsivity: The relative filter transmittance and chip responsivity are measured, in order to characterize the spectral character of the system response. They are also used to determine the effective lamp irradiance, which is given by

$$\overline{E} = \frac{\int E_\lambda \; S_\lambda \; T_1 \ldots T_n \; d\lambda}{\int S_\lambda \; T_1 \ldots T_n \; d\lambda} \quad (1)$$

where E_λ is lamp spectral irradiance at 50 cm, S_λ is CCD relative spectral sensitivity, and T_i is the filter relative spectral transmittance for filter i.

Absolute Radiance: The absolute radiance calibrations are taken as a function of spectral filter and neutral density filter. The resulting calibration constants are determined from

$$C(SP,ND) = \frac{.98\bar{E}}{\pi}\,\frac{50^2}{d^2}\,\frac{1000}{S}\,\frac{Exp}{100} \quad (2)$$

where d is the lamp position, S is the measured signal, and Exp is the exposure. In practice, these constants are determined at a series of lamp positions, and consistencies of better than 0.5% are typically achieved.

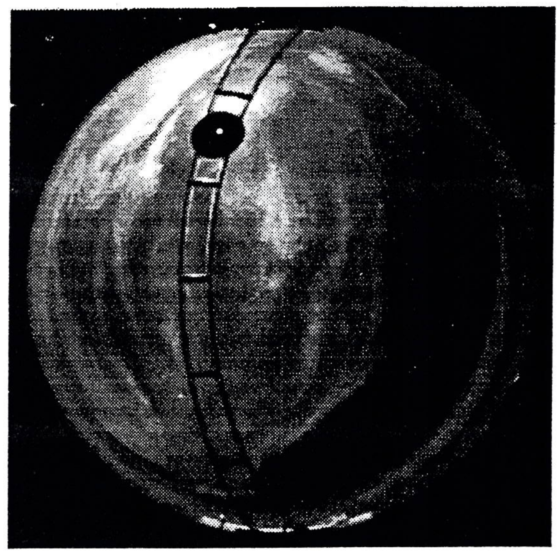
Optical Rolloff: The rolloff function characterizes the off-axis losses due to optical effects such as Fresnel losses.

An angular calibration is used to determine the relationship between the pixel position in image space and the angular position in object space.

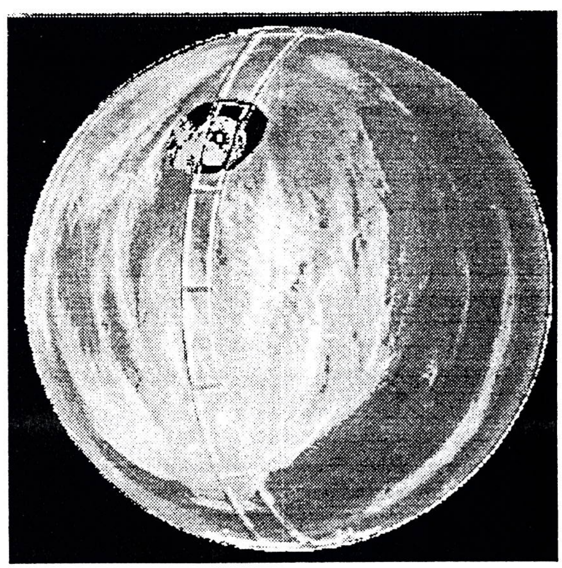
These calibrations are analyzed and may be applied to the field data (a discussion of this application is beyond the scope of this paper). As a result, each image from the field, when calibrated, can provide approximately 200,000 measurements of the sky and cloud radiances as a function of angular position in the sky. We anticipate that these will be very useful for a variety of applications such as evaluation of the impact of cloud and radiance distribution on the ground-based irradiances, and better modeling of sky radiance for fenestration and for military target contrast studies.

5. THE CLOUD ALGORITHM AND CLOUD DECISION IMAGE

The cloud decision algorithm is designed to identify the presence of clouds on a pixel by pixel basis. It makes this determination primarily from the spectral character of the sky, as measured by the red/blue ratio. Figs. 5 and 6 show a cirrus case, and a black/white version of the cloud algorithm result. The cloud algorithm first applies the appropriate calibration factors to the 16-bit data, and then ratios the red and blue images to provide a ratio image. The ratio is thresholded to identify the opaque clouds; thus opaque clouds are identified by their spectral character. For the thin clouds, the site-dependent spectral character of the clear sky is determined, as a function of zenith angle, azimuth with respect to the sun, solar zenith angle, and haze load. This clear sky background ratio is extracted from data taken in the field at the field site; thus the algorithm must be trained using site data.



Red image 02/14/97 2005
Figure 5



Cloud Decision image (grey-scale rendition)
Figure 6

When field data are processed, the haze load for the image is determined from the imagery, and the ratio data are then ratioed with respect to the clear sky background. The algorithm identifies a pixel as thin cloud if the field image ratio exceeds the background clear sky ratio (for that pixel and time) by 20%. Thus a pixel is identified as thin if its spectral signature is not as high as that of an opaque cloud, but is significantly different from that of the clear or hazy sky at the same look angle and solar/lunar angle. Although the thin cloud determination shown in Fig 6 is quite good the real-time version of this algorithm does not yet include an automated determination of the haze load, so it is used primarily for opaque cloud determination at this time.

The results of the cloud decision process are saved as an image. In the image, pixels which are identified as clear are given a value within a certain range, and are colored blue. Pixels identified as thin clouds are given a value in a different range, and colored yellow or light blue, and pixels identified as opaque clouds are given a value in a third range, and colored grey or white. The texture of the original image is retained, and included in the cloud decision image, to allow the user to make a more effective visual assessment of the cloud decision image.

From the cloud decision images, the cloud cover over the full sky may be computed from those pixels identified as opaque cloud or no cloud. Other results can include cloud distribution, motion, and size parameters. Statistical calculations such as CFLOS probabilities can be extracted from extended data bases of the data. The cloud decision images may be used in conjunction with the sky radiance images to provide an assessment of radiance distributions within clouds.

6. SUMMARY

The Day/Night Whole Sky Imagers provide high precision digital imagery of the cloud field during both daytime and nighttime. These images are similar in concept to radiance distributions acquired by scanning radiometers, however they provide much higher resolution, and the data are simultaneous. The data are used both for cloud cover assessment and for measurement of radiance distribution. The capability for determination of the absolute radiance distribution is just emerging, as is the acquisition of data in both the visible and the NIR.

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