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AUTOMATED WHOLE SKY IMAGERS FOR DAY AND NIGHT CLOUD FIELD ASSESSMENT

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SUMMARY

A new 24-hour automated Whole Sky Imager (WSI) has been developed at the Marine Physical Laboratory at Scripps Institution of Oceanography. This system is used for assessment and documentation of cloud fields and cloud field dynamics. The WSI is a ground-based system which monitors the upper hemisphere under lighting conditions of daylight, moonlight, and starlight. It is a visible range, passive, electronic imager acquiring multi-spectral images under fully automated control. From these images, the presence of clouds is assessed using automated cloud decisions algorithms for daylight imagery; night algorithms are in development. This technical note describes the system, designated the Day/Night WSI, including sample imagery and a discussion of the algorithms.

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1. INTRODUCTION

Over a period of nearly ten years, the Marine Physical Lab (MPL) at Scripps Institution of Oceanography has developed a series of imaging systems for assessment of the atmosphere (Johnson, et al, 1986; Johnson, et al, 1989; Shields, et al, 1990; and Shields, et al, 1992). The Whole Sky Imagers (WSI) are automated imagers used for assessment and documentation of cloud fields and cloud field dynamics. The WSI is a ground-based electronic imaging system, which monitors the upper hemisphere. It is a passive, i.e. non-emissive system, which acquires multi-spectral images of the sky dome. From these images, the presence of clouds is assessed using automated cloud decision algorithms.

Clouds are such pervasive features of the atmospheric environment that they have a very significant impact on applications ranging from military test support to global warming research. Requirements can range from a simple need to know the cloud cover fraction at a given point in time and space, to a need to know the locations of clouds within the scene or more complex parameters such as the persistence of cloud free line of sight as a function of look angle.

Whole Sky Imagers provide a determination, at approximately 200,000 points in the upper hemisphere, of the presence of opaque clouds and thin clouds in the line of sight. WSI's may also be adapted to provide calibrated radiance at each of these points. Under fully automated control, the WSI's provide this information with minimal human intervention. The data may be used for statistical analysis of relations between cloud free line of sight and cloud cover, evaluation of persistence and recurrence, and other high resolution spatial and temporal characteristics of the cloud field. The systems are used in military test site support, providing documentation of field conditions during tests such as missile tracking tests. For Global Warming applications, the WSI's will provide cloud cover and cloud distribution information at test sites. These data will be used for studies of cloud radiative forcing and feedback mechanisms, and in understanding relationships between the cloud field and incoming solar radiation at the surface.

Over the last decade, the Optical Systems Group (OSG) at MPL, and formerly at the Visibility Lab, has developed a family of WSI systems, beginning with the fielding of the first two generations, EO System 1 and EO System 2, in 1984. During the late 80's, OSG developed and fielded Day-only WSI's (EO System 5), fully automated systems which acquire image sets every minute for 12 hours per day. These images undergo a series of calibrations and processing by automated algorithms to yield a cloud decision image with 1/3 degree spatial resolution. Several of these daytime WSI's operated in the field over a period of 2 to 3 years per site (Shields, et al, 1991; Johnson, et al, 1991; and Koehler, et al, 1991).

Building on the experience gained with the Day WSI systems, OSG has more recently developed a Day/Night WSI (EO System 6) capable of image acquisition under daylight, moonlight, and starlight conditions (Shields, et al, 1993). This note discusses the Day/Night WSI systems, including control of data acquisition and interpretation of the data.

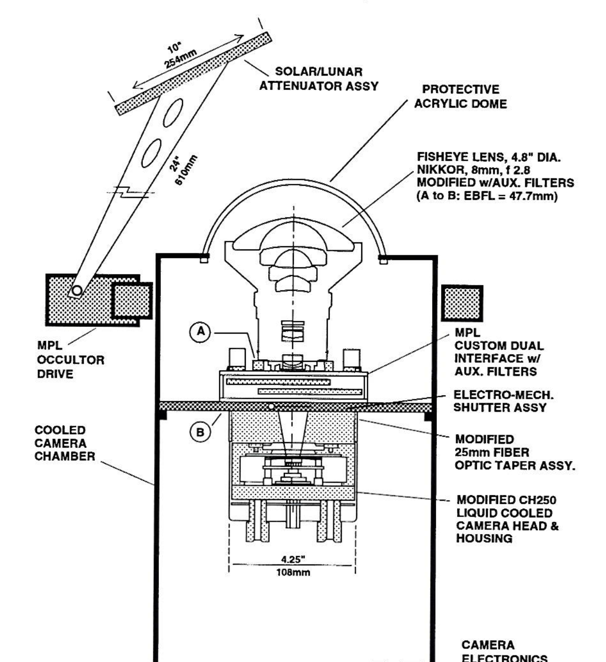
2. OVERVIEW OF THE DAY/NIGHT WSI SYSTEM

The Day/Night WSI is a ground-based electronic imaging system. The sensor package consists of a solid state CCD (Charge Coupled Device) camera, solar/lunar occultor, filter changer, and environmental protection. The control package consists of an IBM PC-compatible computer for communications and system control, a backup archival unit, and an Accessory Control Panel to enable a manual interactive link with the sensor assembly.

2.1 The WSI Sensor

The WSI sensor is illustrated in Fig. 1. The primary components in this figure are discussed below.

FIG. 1
WSI DAY/NIGHT SENSOR ASSEMBLY
(NOT TO SCALE)



The fisheye lens is a Nikkor 8mm f/2.8 lens. It has a full 180 degree field of view for viewing the complete sky dome simultaneously. The lens has equi-distant projection, i.e. the zenith angle in object space is nearly linear with respect to the position of the corresponding pixel in image space.

Like the Day-only WSI, the Day/Night WSI uses an optical filter changer designed by the OSG. There is a significant difference between the optical system in the two WSI's however. The optical system in the Day-only WSI uses an optical relay to convert the fisheye image size and location to the appropriate camera chip format. The lenses which form this optical relay are part of the filter changer in the Day-only WSI.

The Day/Night WSI uses a different concept for converting the fisheye image format. The filter wheels are placed directly between the exit aperture and the back focal plane of the fisheye. The back focal plane is coincident with the surface of a fiber optic taper, which then de-magnifies and transfers the image to the chip. The fiber optic taper is bonded to the chip, for a proximity focus system. The losses and distortions in the taper are minimal, in comparison with relay systems we considered, so that optical quality and sensitivity are preserved.

The optical filter changer contains two independently controlled filter wheels, each containing up to four filters. One wheel is intended for spectral control, the other for flux level control. The standard set-up is currently as follows:

Filter Position	Spectral Wheel	ND Wheel
1	opaque (blocked)	open
2	open	2 log ND
3	650 nm	3 log ND
4	450 nm	optional

Most of the above filter positions also include optically transparent trim filters, to enable pixel registration (i.e. same size image for all possible filter combinations). Spectral position 1 is used for acquiring a dark image, used to correct the raw field image for dark offset and pixel nonuniformity. Spectral 2 is open-hole, and may be used for calibration or for acquisition under rural starlight conditions. Spectral positions 3 and 4 are for acquiring the red and blue images. The use of this filter pair has enabled development of cloud algorithms based on the spectral character of the sky scene. Neutral Density position 1 is used for night acquisition, 2 is for twilight, and 3 is for daytime. Filter position 4 on the ND wheel may be used for optional test configurations.

This selection of filters is somewhat different from that used in the Day WSI. In particular, the Day WSI used two pairs of red and blue filters. This was due to the limited dynamic range of the CID (Charge Injection Device) camera which is used in the Day Only WSI. Since the CID had a useful dynamic range of approximately 1.2 logs, it was necessary to use a second filter pair offset by .5 log to yield a dynamic range of approximately 1.7 logs. The Day/Night WSI uses a CCD with a dynamic range of approximately 3 logs or more, and the use of a second filter pair is unnecessary.

The Day/Night WSI's electronic camera is a Photometrics Slow Scan CCD. In our early development of nighttime capability, we tested a number of options, including on-chip integration with a CID camera, and use of an image intensifier. We found on-chip integration to be very non-linear, particularly as the sensor chip aged. Our image intensifiers proved to be noisy and unstable in our test applications; they also may be damaged by exposure to excess flux, which made their use in unattended field situations problematic.

Following tests of several CCD cameras, we chose to go with a Photometrics slow scan camera. This camera has outstanding noise and sensitivity characteristics as well as high image quality. Its very low noise and high sensitivity allow acquisition of night imagery, even under starlight conditions. Its 16 bit digitization, in combination with the low readout noise, allow for an outstanding combination of large dynamic range with fine radiometric resolution. However, in slow scan camera operations, data readout is far slower than in the earlier RS-170 class video systems such as used in the Day WSI. What you trade for of course is nighttime capability with high image quality.

The camera housing shown in Fig. 1 is temperature stabilized. It is sealed and purged with dry nitrogen at a slight positive pressure for protection of the sensor elements from moisture.

The tracking solar/lunar occultor is a dual drive occultor, with separate control of the azimuth drive and zenith drive. The computer logic supplies the appropriate occultor gear angle as a function of date and time, and the occultor is driven (automatically) to the proper position. Most of the occultor is opaque, however the central portion consists of a 4 log neutral density filter, so that the sun or moon position may be detected. This aids in validation of computer clock time, WSI leveling, and lens geometric calibration.

As shown in Fig. 2, the WSI sensor and camera chamber are further protected by an environmental enclosure. The system includes a chiller assembly, which cools the camera chamber. In addition, the chilled liquid is provided to the hot side of the TE (thermo-electric) cooler which cools the sensor chip, thus further enhancing the low noise characteristics of the CCD. (Nitrogen cooling is not required.) The environmental enclosure also houses the camera electronics unit, and coolant flow monitor.

Fig. 2
WSI DAY/NIGHT SENSOR WITH ENVIRONMENTAL HOUSING
(NOT TO SCALE)

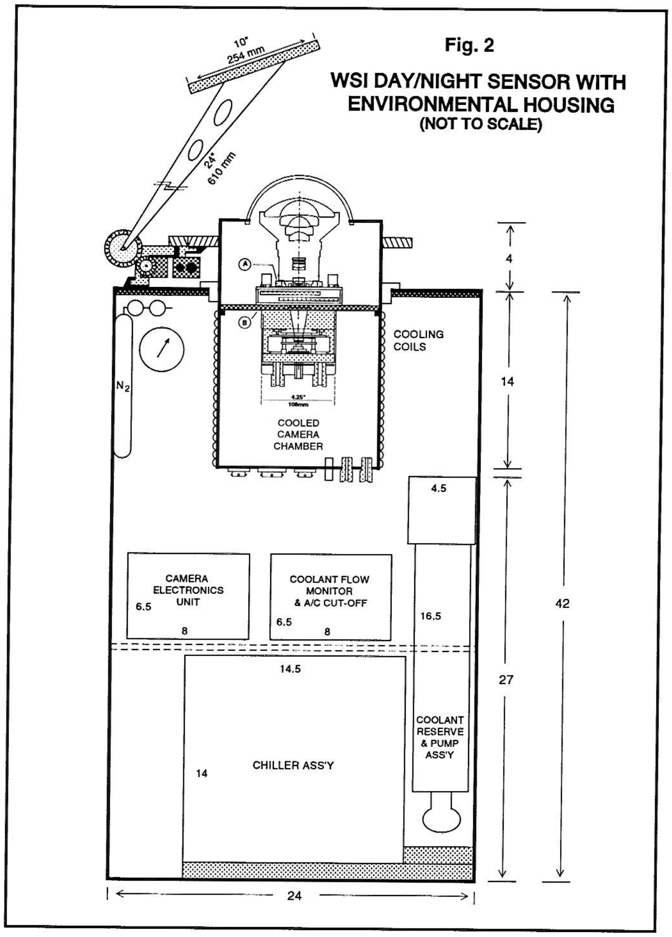
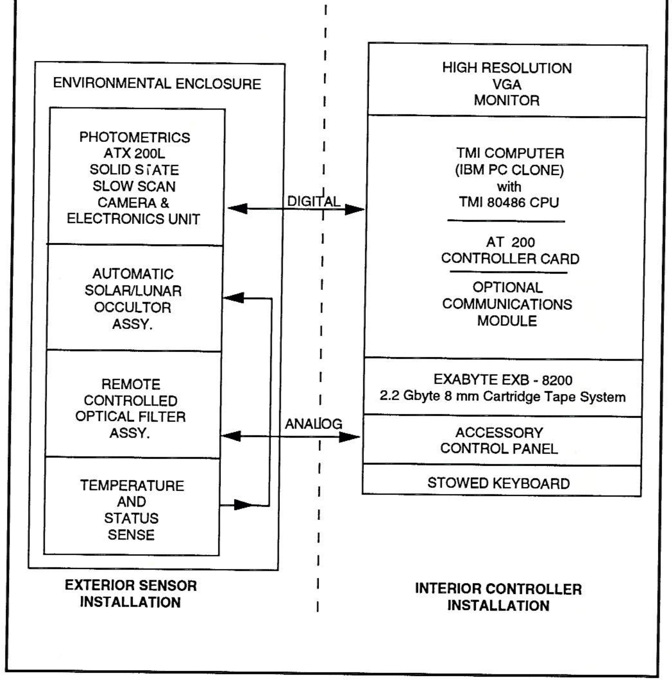


Fig. 3
DAY/NIGHT WSI
HARDWARE BLOCK DIAGRAM



2.2 The WSI Controller

The WSI exterior sensor system is connected to a controller, consisting primarily of electronics and the computer package. This controller must be in an office environment or equivalent protected environment. These units are normally connected by 100-foot cable. Fig. 3 illustrates the primary components of both the exterior sensor and the interior controller, and their connection.

In addition to the PC computer and monitor, the controller includes an Accessory Control Panel (ACP). This ACP enables control of the filter changer and occultor either manually or through computer control. The controller also includes an Exabyte tape backup system with a data storage capacity of 2.3 Gbytes.

3. WSI DATA AND ACQUISITION

3.1 Sample Imagery

A sample Day/Night WSI image is shown in Fig. 4. In this illustration, the zenith is in the center, with the horizon on the edge of the round image. The south is at the top, and east is to the right. The black square near the right is the solar/lunar occultor. When not obscured by clouds, the sun is imaged through the 4 log neutral density filter in the occultor. The red, blue, and dark imagery may be processed to yield a cloud decision image, as shown in Fig. 5. Regions of this image which have been identified by the automated algorithm as clear sky are false colored blue. Opaque and thin clouds are identified with white and yellow respectively. A cloud decision is made independently at each pixel location.

A moonlight image acquired by the WSI on-site at Kirtland AFB, NM, is shown in Fig. 6. In this image, the occultor is nearly overhead, with the moon imaged through the 4 log neutral density filter. Nearby buildings and terrain may be seen on much of the image edge, with clouds to the north (bottom) of the image. A few stars appear in the image to the east (right). Under moonlight, the path radiance or moonlight scattered into the path of site masks most stars.

conditions, it is necessary currently to use the open hole (no spectral filter) acquisition with approximately 1 minute exposures.

The flux control algorithm is designed to allow the system to automatically determine the appropriate instrument settings to enable acquisition of on-scale data. In the Day-only WSI, this flux control was based on minute-by-minute assessment of the prevailing light levels. The Day/Night WSI uses a different scheme, which is essentially predictive, in order to handle the very quickly changing flux levels during the hours near sunrise and sunset.

The data illustrated in Fig. 9 were used as the first estimate of relative changes in downwelling irradiance. For flux control, we are more interested in the average sky radiance than in the downwelling irradiance of the sky. For this reason, the diffuse irradiance, which is more closely related to the average sky radiance, was estimated from the downwelling irradiance curves in Fig. 9, using Kondrat'yev (1965). For characterizing the flux levels under moonlit conditions, the algorithm also makes corrections for earth-lunar distance and for moon phase angle (Haphe, 1963).

Combining the expected radiant field information with the operating characteristics of the camera, a determination was made of the approximate desired minimum signal for various conditions. From this, tables of neutral density filter and exposure setting as a function of solar zenith angle, lunar zenith angle, lunar phase and lunar distance were generated for use by the system. The selected exposure/ND filter is changed whenever the flux is expected to change by approximately .2 logs.

4. AUTOMATED CLOUD ASSESSMENT

Once quality imagery is acquired, it is desirable to make an automated, pixel-by-pixel determination of the presence of clouds in the images. This might appear to be an easy task, since the clouds are so obvious to a human viewing the properly displayed images. However, to generate an algorithm which identifies clouds consistently over many months of data, at a variety of sites, is not trivial.

In our early work with the cloud algorithms (1984), we determined that radiance thresholding is generally not adequate, because clouds can often be darker than the adjacent sky. Edge detection provided additional information, however many of the clouds have quite diffuse edges which are not easily identified with the techniques used in the early tests. Similarly, texture analysis provided useful but inadequate information. Detection based on the red/blue ratio, proved to be quite effective however. This technique essentially allows one to base the cloud decision on the color, or spectral signature as defined by this ratio. The red/blue ratio is the basis of the current daytime cloud decision algorithm.

The cloud decision algorithm is illustrated conceptually in Fig. 11. In order to compute the ratio images, one must first acquire radiometric calibrations to characterize sensor performance. Calibrations of the dark image characteristics, temporal and spatial signal variances, linearity as a function of exposure, linearity as a function of flux level, and relative response as a function of spectral and neutral density selection have been acquired and evaluated for an existing Day/Night WSI. These results are used in the ratio computation algorithm. This ratio computation procedure is simpler than with the older Day-only WSI, due to the improved linearity and pixel registration of the current WSI's.

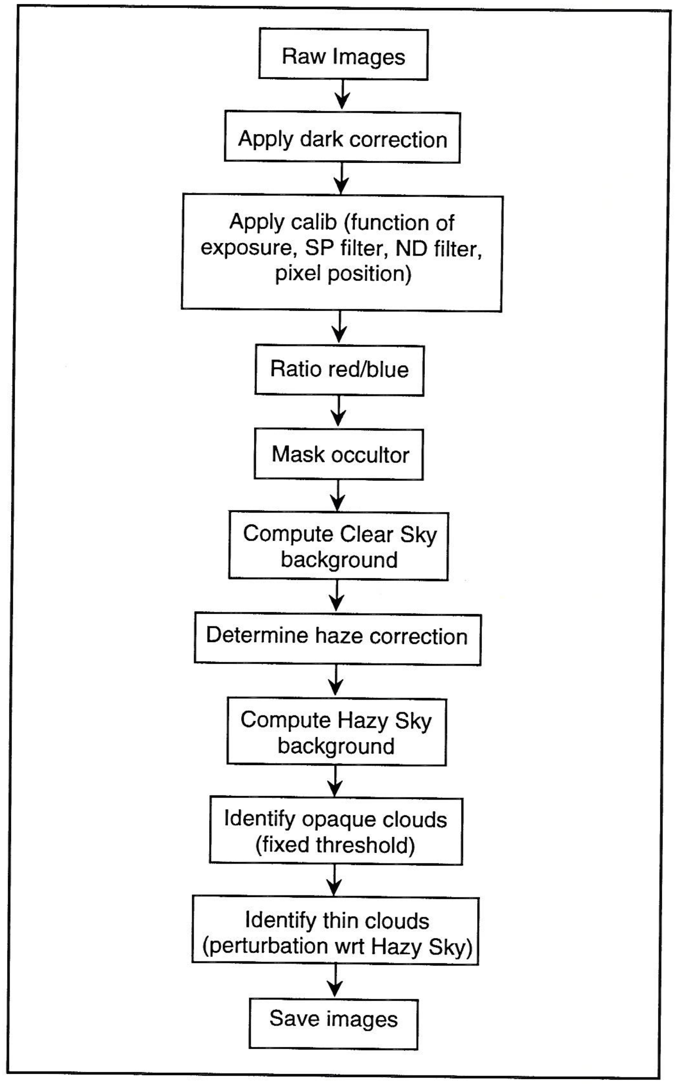


Fig. 11. Cloud Data Processing Conceptual Flow Chart

cloud decision images from a set of data acquired during a 28 minute interval as a stratocumulus band passed overhead.

There are several features of this cloud identification technique which should be noted. First, unlike schemes involving human evaluation of images, the technique is both fast and consistent. Secondly, through application of the calibration corrections, most of the bias due to camera characteristics such as non-linearity is removed. Third, through use of the ratio technique, as opposed to an identification based on radiative brightness, one correctly identifies even clouds which are darker than the sky background. Finally, through correction of the background sky ratio for aerosol load and directional variance, the system avoids much of the directional bias inherent in human assessment; for example, a cirrus streak from an aircraft is correctly identified both upsun and downsun.

For moonlit images, it should be possible to use a cloud decision algorithm which is conceptually similar to that used in the Day WSI. A study of night radiance distributions acquired by our group in 1968 and 1969 has been made to evaluate the red/blue ratios under a variety of conditions, (Gordon, 1989). This study indicates that for full moon to quarter moon lighting conditions, the red/blue ratio should be a reasonably good indicator of clouds, but for starlight conditions the spectral character of the sky is quite different, and a different algorithm will be required. Development of the moonlight algorithm, along with characterization of the contamination of the light field due to terrestrial sources (such as urban lights) is currently under development.

5. CONCLUSION

Both the Day/Night Whole Sky Imagers and the Day WSI's, developed by the Marine Physical Lab, acquire imagery appropriate for automated identification of cloud fields. Depending on sponsor requirements, these WSI's may either yield a data archive for post processing, or yield near-real time results. The latest version of the WSI units acquires imagery not only during the daytime, but under moonlight and starlight conditions, for full 24-hour automated data acquisition.

In use by the military for several years, these systems yield data for determination of cloud cover, as well as cloud field spatial characteristics such as angular distributions of cloud free line of site. Statistical information such as the frequency of cloud obscuration of direct solar flux as a function of cloud cover and solar zenith angle are readily extracted (limited only by the mechanics of dealing with a large data base). Temporal studies such as evaluation of persistence and recurrence, as well as cloud development vs. translation studies become feasible. Finally, if full absolute radiometric calibrations are obtained prior to fielding the system, the upper hemisphere absolute radiance distribution may be extracted from the data. As these systems continue to develop in capability, flexibility, and convenience, they should continue to have important applications including military test support and global warming research support.

6. ACKNOWLEDGMENTS

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