AUTOMATED WHOLE SKY IMAGERS FOR CONTINUOUS DAY AND NIGHT CLOUD FIELD ASSESSMENT

Janet E. Shields, Richard W. Johnson and Monette E. Karr
Marine Physical Laboratory
University of California, San Diego
San Diego, California 92093-0701, USA

A new 24 hour, fully automated Whole Sky Imager (WSI) has been developed for assessment of clouds from daylight through dark moonless night conditions. The WSI is a ground based passive system which monitors the full 2π upper hemisphere, providing as output products, fully digitized 512x512 images at 16 bit resolution. This new Day/Night WSI, in a manner similar to its daytime-only predecessor, acquires, processes and archives visible spectrum imagery customized for the assessment and documentation of cloud fields and cloud field dynamics. Unlike its predecessor, this new system acquires its multi-spectral imagery under ambient lighting conditions from full daylight down through moonlight to clear starlight. Automated cloud algorithms enable the detection of thin and opaque clouds against a variety of sky backgrounds. Early versions of the new night-capable WSI are already in use by Army, Navy, and Air Force, and units are in development for global warming research.

1. INTRODUCTION

The Day/Night Whole Sky Imagers developed by the Marine Physical Lab (MPL) at Scripps Institution of Oceanography represent a major advancement in the capability of MPL's family of Whole Sky Imagers (WSI's). These systems are being used to acquire cloud data for the full upper hemisphere, under both moonlight and starlight conditions. Retaining the daylight capabilities of their predecessors, these systems acquire images at user-determined intervals, automatically adjusting for the light levels as conditions range from full sunlight to starlight. With their high spatial and temporal resolution, they are proving very useful in military tests involving characterization of the quickly changing cloud field.

Over a period of nearly ten years, MPL 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, automated cloud decision algorithms are used to assess the presence of clouds at approximately 200,000 points in the upper hemisphere. 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.

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.

The Optical Systems Group (OSG) at MPL, and formerly at the Visibility Lab, fielded the first two generations of WSI's, EO System 1 and EO System 2, in 1984. During the late 80's, OSG developed and fielded several Day-only WSI's (EO System 5). These fully automated systems 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 which operated in the field over a period of 2 to 3 years per site are still operational (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 the 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. ACQUISITION OF CLOUD DATA AT NIGHT

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 Sample Imagery

A sample moonlight image acquired by the WSI on-site at Kirtland AFB, NM, is shown in Fig. 1. 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 center is the

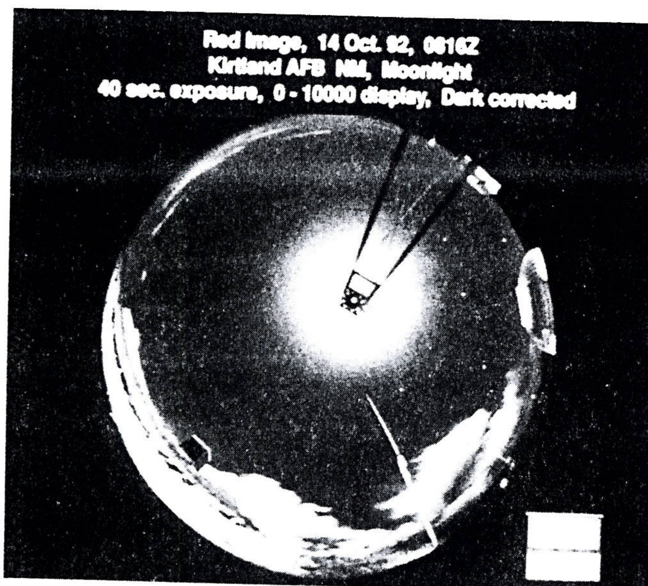


Fig. 1 WSI Raw Data Image Acquired with Moonlight at 650 nm

solar/lunar occultor. When not obscured by clouds, the sun or moon is imaged through the 4 log neutral density filter in the occultor. 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. In this 40-second exposure image acquired at 650nm wavelength, all portions of the scene are well on scale, including the clouds which are bright white in the reproduction.

Sample images acquired by the WSI on-site at White Sands Missile Range, NM, are shown in Figs. 2 and 3. These images were acquired under no-moon conditions with 60 second exposures. Figure 2 shows a clear starlit sky, de-enhanced slightly to emphasize the constellations. In Fig. 3, a cloud field encroaching from the northeast covers approximately half the sky dome. The Milky Way may be seen in the upper half of the image. The

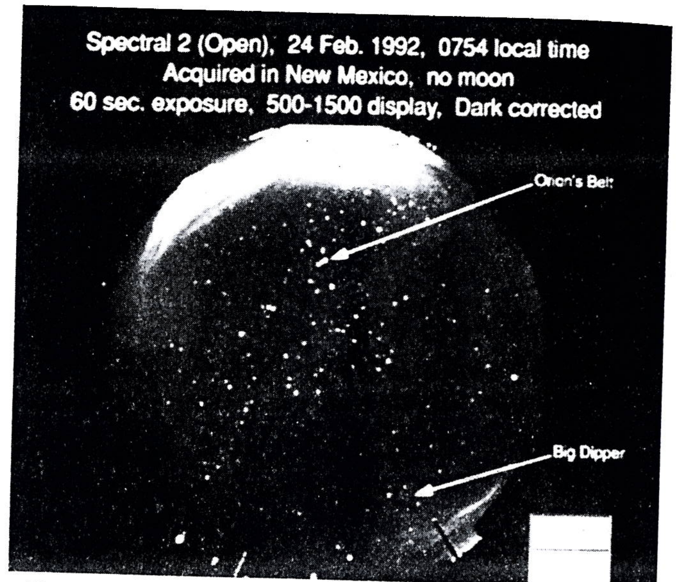


Fig. 2 Clear Starlight Image Enhanced to Emphasize Star Constellation Patterns

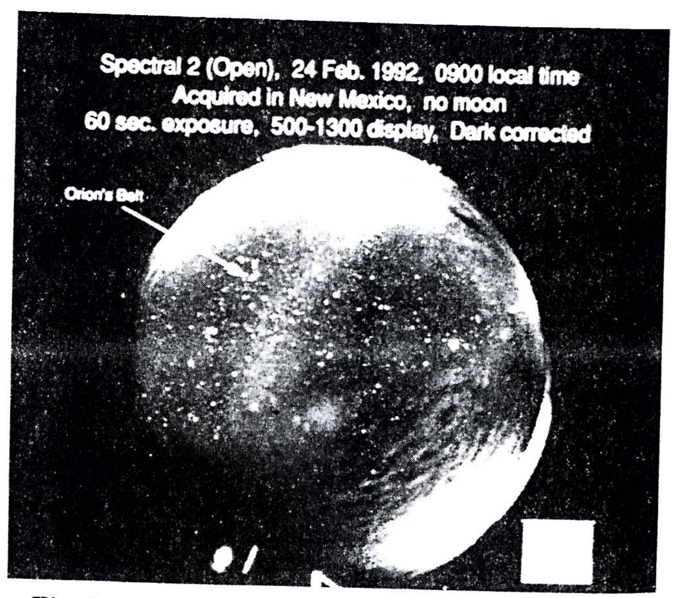


Fig. 3 WSI Raw Data Image Acquired with Starlight in Open-hole Configuration

lights to the south (near the top of the image) are from the sky light over El Paso, approximately 40 miles from the site. Note that in the clear regions, many more stars are visible than may be seen in Fig. 1 due to the reduced path radiance under no-moon conditions.

An interesting feature of the camera performance may be seen in Fig. 3. With 16 bit digitization, the system has approximately 65,000 gray levels. This gives the system a useful radiometric range of over three logs, while retaining very good radiometric resolution. In this particular image, in order to show the features such as the cloud texture, the gray level range from 500 counts to 1300 counts has been displayed. Anything above 1300 is shown in Fig. 3 as white, and anything below 500 appears black. The white areas near the top of the image which appear to be offscale bright in this reproduction are actually onscale in the digital image, just as the black areas near the bottom are onscale in the digital image. This large digital range, in combination with the low noise, allows the system to acquire features at a large range of brightnesses, while retaining features which occupy a narrow portion of this brightness range.

2.2 WSI Data Acquisition

One of the important design criteria for the Day/Night WSI is the large range of flux levels the system must be able to deal with. Figure 4 shows the naturally occurring illuminance levels under a variety of lighting conditions. These data are from the work of Brown 1952, and are consistent with irradiance measurements acquired by our group at the Visibility Lab over a period of many years. In Fig. 4, the daytime illuminance conditions the Day WSI has had to deal with are shown in the top two curves on the right side of the plot. These represent clear to dark storm conditions for sun zenith angles 0 to 90 degrees. The Day/Night WSI is operational through quarter moon conditions shown on the bottom right curve, and down to the starlight conditions shown on the left side of the plot. This represents approximately a 9 log range of lighting conditions. The sensor is designed to obtain the necessary sensitivity range by using the approximately 3 to 3.5 log sensitivity of the camera chip, approximately 3 logs range from exposure control, and approximately 3 logs range through neutral density filter control.

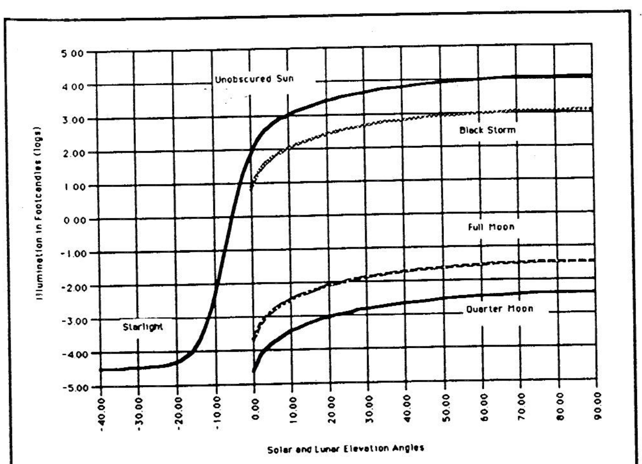


Fig. 4. Natural Illumination Levels.
These measurements, from Brown 1952, illustrate flux conditions the Day/Night WSI should encounter.

3. THE DAY/NIGHT WSI

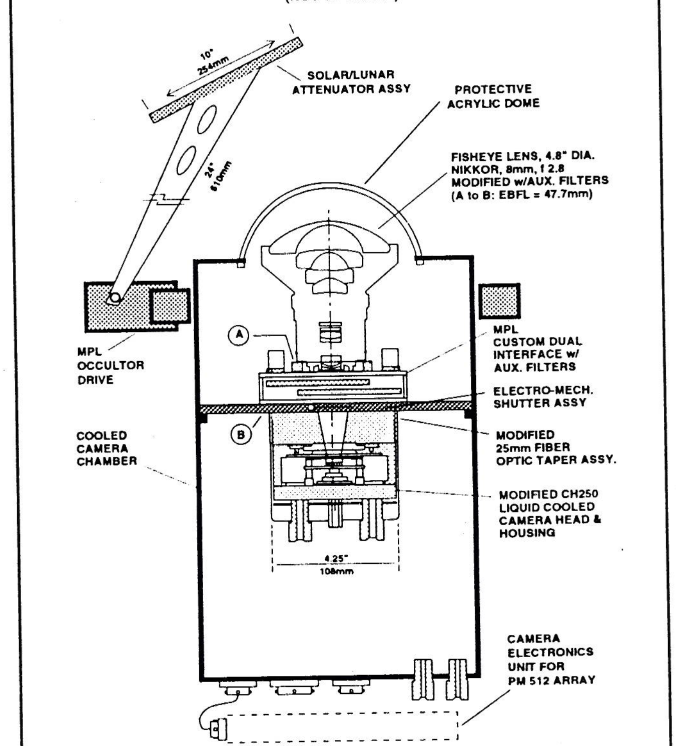
3.1 The WSI Sensor

The WSI sensor is illustrated in Fig. 5. The primary components in this figure are discussed below.

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 radial 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

Fig. 5
WSI DAY/NIGHT SENSOR ASSEMBLY
(NOT TO SCALE)



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 spectral filter positions include open-hole, used for acquisition under rural starlight conditions, as well as a red and blue filter pair. The use of this filter pair has enabled development of cloud algorithms based on the spectral character of the sky scene. The second filter wheel contains neutral density filters used as part of the control of input flux levels.

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 the Photometrics slow scan camera. This camera's 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.

The camera housing shown in Fig. 5 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.

3.2 The WSI Controller

The WSI exterior sensor system is connected to a controller, consisting primarily of electronics and the computer package. 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.

4. AUTOMATED ACQUISITION ALGORITHMS

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. 4 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. 4, 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 (Hapke, 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.

5. AUTOMATED CLOUD ASSESSMENT

The cloud decision algorithm used during daylight is quite similar to that used with the Day-only WSI, as discussed in Koehler (1991). This algorithm first applies a number of radiometric calibration corrections, which are system-dependent, in order to remove such effects as the varying passbands of the spectral filters. The red and blue images are then ratioed pixel by pixel (with any necessary corrections for image size).

Once the calibration-corrected ratio is computed, the opaque clouds are identified on the basis of this ratio alone. A simple threshold technique is used in which pixels that exceed a specified ratio are identified as opaque cloud. In other words, the opaque cloud discrimination is based on spectral signature, as defined by the red/blue ratio.

Thin clouds are not defined with a specific spectral signature, but rather as a given deviation from the spectral signature of the background sky. In simpler terms, thin clouds are not necessarily white, however they are whiter than the sky background in a given direction. The sky ratio varies both directionally (i.e. as a function of both look angle and solar zenith angle) and as a function of visibility.

The thin cloud determination uses both a site-dependent characterization of the directional aspects of the sky background ratio, and a minute-by-minute determination of the haze impacts. A sample raw daytime image, and its associated cloud decision image (the result of the cloud decision algorithm) are shown in Figs 6 and7. In Fig. 7, the white regions are opaque cloud, and the small darker grey regions near the opaque clouds are thin cloud.

The day cloud algorithm has been applied to much of the Day WSI data base A data base of approximately 900 Gigabytes of raw image data (approximately 4600 data days) has been generated with Day WSI's. Of this data, 14 months at each of 4 stations have been processed to the cloud decision image (Johnson, 1991). The results compare quite well to the standard observer (Shields, 1990, and Koehler, 1991).

The prototype moonlight algorithm is quite similar to the daylight algorithm, since the scattering processes and resulting sky color are quite similar under moonlight. The primary change is the requirement to characterize and remove the impact of the terrestrial light sources. Starlight algorithms have not yet been developed, and will surely be an item of research in future years.

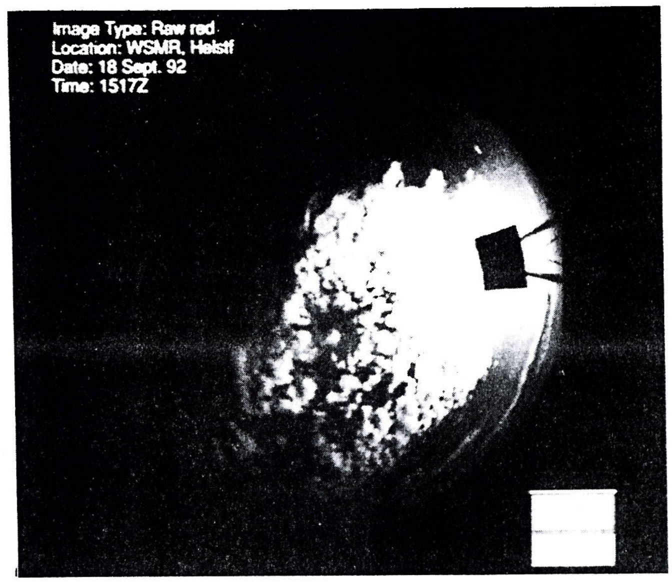


Fig. 6 WSI Raw Data Image Acquired with Daylight at 650 nm

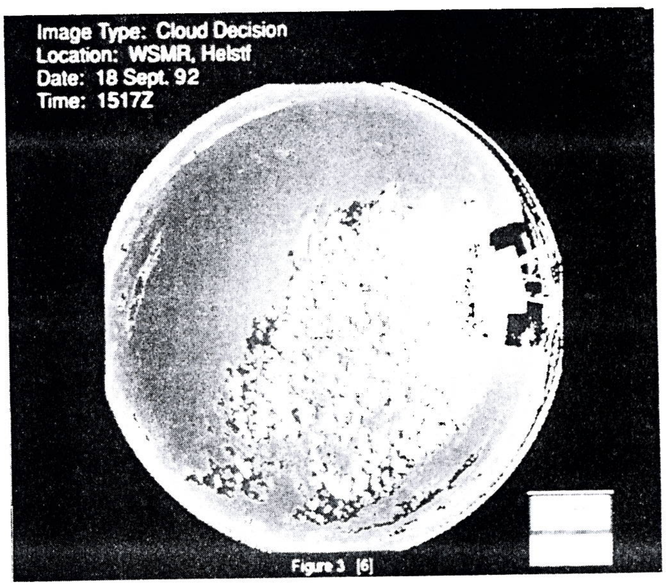


Fig. 7 Processed Cloud/No Cloud Decision Image

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.

6. APPLICATIONS

The current use of the WSI systems by the military primarily involve site support for night operations. Tracking tests are an example, in which the ability of a tracking system to retain lock-on with the target is partly influenced by environmental factors. By superimposing the track of the target directly onto the WSI image (with the acquisition software), the user is able to precisely determine the presence of clouds along the track during the time of the test. This has proven especially useful in low light conditions when the imaged clouds are often not visually detectable.

Other uses involve monitoring approaching clouds during night tests involving phase front distortion studies. Clouds in the path of sight are evaluated regarding their impact on seeing conditions by telescope, and transmission of laser energy to satellites. The impact of the visually undetected thin cirrus clouds are of particular interest in these studies.

A very wide range of potential military applications exist, including studies of cloud free line of site statistical behavior. The systems may be used for satellite ground truth studies, as well as evaluation of the accuracy of ceilometer-determined cloud cover and its impact on flight operations. With conversion to a 220 degree field of view lens, the systems can monitor not only clouds, but incoming objects below the horizon, for naval operations. With slightly different spectral filter choices, the monitoring and characterization of sub-visual cirrus become practical.

In its current state, the Day/Night WSI provides an absolutely unique capability. As these systems continue to develop in capability, flexibility, and convenience, they should continue to have important applications in test support and research for both the military and the civilian community.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Hapke, B. W., 1963: "A theoretical Function for the Lunar Surface", Journal of Geophysical Research, Vol. 68, No. 15, 4571-4585.

Johnson, R. W., W. S. Hering, and J. E. Shields, 1986: "Imagery Assessment for the Determination of Cloud Free Intervals", University of California, San Diego, Scripps Institution of Oceanography, Visibility Laboratory, Atmospheric Visibility Technical Note No. 200.

Johnson, R. W., W. S. Hering, and J. E. Shields, 1989: "Automated Visibility and Cloud Cover Measurements with a Solid-State Imaging System", University of California, San Diego, Scripps Institution of Oceanography, Marine Physical Laboratory, SIO 89-7, GL-TR-89-0061, NTIS No. ADA 216906.

Johnson, R. W., J. E. Shields, and T. L. Koehler, 1991: "Analysis and Interpretation of Simultaneous Multi-Station Whole Sky Imagery", University of California, San Diego, Scripps Institution of Oceanography, Marine Physical Laboratory, SIO 91-33, PL-TR-91-2214.

Koehler, T. L., R. W. Johnson, and J. E. Shields, 1991: "Status of the Whole Sky Imager Database", Proceedings of the Cloud Impacts on DOD Operations and Systems - 1991 Conference.

Kondrat'yev, K. YA., 1965: "Actinometry", NASA TT F-9712, Translation of "Aktinometriya", Gidrometeorologicheskoye Izdatel' stvo, Leningrad, 1965.

Shields, J. E., T. L. Koehler, M. E. Karr, and R. W. Johnson, 1990: "Automated Cloud Cover and Visibility Systems for Real Time Applications" Optical Systems Group Technical Note No. 217, University of California, San Diego, Scripps Institution of Oceanography, Marine Physical Laboratory.

Shields, J. E., R. W. Johnson, and T. L. Koehler, 1991: "Imaging Systems for Automated 24-Hour Whole Sky Cloud Assessment and Visibility Determination", Proceedings of the Cloud Impacts on DOD Operations and Systems - 1991 Conference.

Shields, J. E., R. W. Johnson, and M. E. Karr, 1992: "An Automated Observing System for Passive Evaluation of Cloud Cover and Visibility", University of California, San Diego, Scripps Institution of Oceanography, Marine Physical Laboratory, SIO 92-22, PL-TR-92-2202.

Shields, J. E., R. W. Johnson, and T. L. Koehler, 1993: "Automated Whole Sky Imaging Systems for Cloud Field Assessment", Fourth Symposium on Global Change Studies, 17 - 22 January 1993, Anaheim, CA. Published by the American Meteorological Society, Boston, MA.