ARM TR-043

Whole-Sky Imager Handbook

January 2005

Atmospheric Radiation Measurement Climate Research Facility
U.S. Department of Energy

Work supported by the U.S. Department of Energy
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1. General Overview

The whole-sky imager (WSI) is an automated imager used for assessing and documenting cloud fields and cloud field dynamics. The WSI is a ground-based electronic imaging system that monitors the upper hemisphere. It is a passive, i.e., non-emissive, system that acquires images of the sky dome through three spectral filters (neutral, red, and blue). From these sky images, we can assess the presence, distribution, shape, and radiance of clouds over the entire sky using automated cloud decision algorithms and related processing. The current WSI model (EO System 6) is capable of image acquisition under daylight, moonlight, and starlight conditions.

2. Contacts

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3. Deployment Locations and History

WSIs are currently located at the Southern Great Plains (SGP), North Slope of Alaska (NSA), and Tropical Western Pacific (TWP) sites.

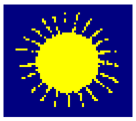
4. Near-Real-Time Data Plots

Barrow, Alaska Quicklooks

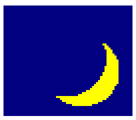
Atqasuk, Alaska Quicklooks

5. Data Description and Examples

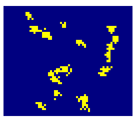
Observed Data:



Sample Daylight image. Note that the occultor design on this imager is different from the design employed at SGP and TWP.

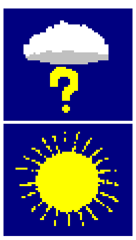


Sample Moonlight image. Note that the occultor design on this imager is different from the design employed at SGP and TWP.



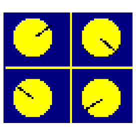
Sample Starlight image.

Calculated data:



Sample cloud decision image determined from the red/blue ratio image and the ratio threshold calibration values along with the corresponding red daylight image.

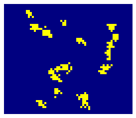
Time series (MPEG movies):



This time series (2MB) is from the alpha test for unit WSI02. The data were taken 31 Jan 1996 between 1748Z and 2358Z. Notice the modified occultor for ARCS1. This occultor has only one degree of freedom because the trolley drive has been eliminated, and it has been sized/positioned to allow continuous operation without adjustment.

Interesting/Unusual Data:

This section will highlight interesting/unusual data that are worthy of special attention because they demonstrate some physical phenomenon or they serve as illustrative examples for features of the WSI.



A Starlight image taken near a high-power laser source used in atmospheric studies and compensated imagery studies. (Note the laser beam in the upper half of the image).

5.1 Data File Contents

5.1.1 Primary Variables and Expected Uncertainty

The WSI measures the sky radiance in approximately 1/3 increments over the entire sky dome. The measurements are made in two narrow spectral regions centered at 650 nm and 450 nm. The sky radiances are acquired as two 16-bit images and are used to determine the presence of opaque clouds and thin clouds in the line of sight on a pixel-by-pixel basis. These cloud data are used to calculate the following cloud cover and statistical quantities:

1. Sector cloud cover values over the full sky and in the following nine sectors:
    - a 10° circle at the zenith
    - four quadrants running from 0° to 45° zenith angle
    - four quadrants running from 45° to 90° zenith angle.

2. Kegelmeyer code:
    - Global (1) Statistics:
        - cloud cover fraction
        - cloud path length mean and standard deviation
        - clear path length mean and standard deviation.

    - Per-Cloud (2) Statistics:
        - number of clouds
        - cloud area mean and standard deviation
        - cloud perimeter mean and standard deviation
        - cloud circularity (3) mean and standard deviation.

    Notes:
    (1) All pixels labeled cloud or clear are included in these statistics.
    (2) Clouds that are not entirely visible (i.e., clouds that "touch" the edge of the field of view or the edge of the occultor/occultor arm) are not included in these statistics.
    (3) Circularity is defined as the ratio of the square of the perimeter to the product of 4PI and the area.

The sector cloud cover values are the fraction of the sector containing cloud pixels. The cloud statistical quantities have the units of pixels if no cloud height is assumed; otherwise, they are in the same units as the cloud height.

5.1.1.1 Definition of Uncertainty

There are three primary types of output generated by the WSI: 1) calibrated radiance distributions, 2) quantities such as cloud cover derived from the cloud algorithm results, and 3) visual imagery intended for visual assessment. Each of these outputs are discussed below.

Radiometric Data

The primary source of uncertainty in the radiometric data is the uncertainty of the calibration lamps. For a visible system requiring knowledge of the spectral lamp output and not just total lamp output, lamps are typically accurate to about 3%. With these lamps, net accuracies of 5% are normally achievable. Positioning accuracy is generally 1 when fielded by experienced teams, with a precision of 1/3. Positioning accuracy can be checked and corrected for, if necessary, using the measured sun positions.

Cloud Cover

Quantities such as cloud cover depend on the accuracy of the cloud algorithm. The algorithm works quite well for opaque clouds. bThin clouds are more difficult to characterize because of the difficulty in assessing a very thin cloud with respect to a fairly thick haze. In-house processing has normally been quite accurate, but for the near-real-time code being fielded with the instruments, only the opaque results will be presented until the thin cloud algorithm can be verified or improved for use in totally autonomous mode.

Interpreting Images Visually

When used for visual assessment, the red images are processed for easier viewing. (See windowing in the Theory of Operations, Section 7.2.) While this process introduces no errors, it is possible to misinterpret the resulting images. Specifically, data which appear offscale bright or dark are usually only outside the displayed range, and not actually offscale. Similarly, if features appear to be too dim to see clearly, they can usually be brought out by selection of a narrower display range. It is important for the user to check the image time, and know whether the image was taken under sunlight, moonlight, or starlight. It will be a site responsibility to be sure the instrument is shadowed from extraneous bright lights so that the night sky will be imaged properly.

5.1.2 Secondary/Underlying Variables

This section is not applicable to this instrument.

5.1.3 Diagnostic Variables

This section is not applicable to this instrument.

5.1.4 Data Quality Flags

The following (Table 1) lists the flags applied to the data, the normal operating ranges for each parameter, and the parameter values that generate a flag.

Table 1.

Function	Normal	Yellow Flag Level	Yellow Flag Code	Red Flag Level	Red Flag Code
CCD chip temperature (?C)	-35	> -30	1	> 0	1
Environmental housing temperature (?C)	16	> 32	2	> 49	2
Coolant flow through camera (gpm)	0.25	0.125	3	≤0.09	3
Camera housing temperature (?C)	16	> 32	4	> 49	4
No camera response (If the camera does not respond for any one grab, a red flag is set)	---	---	---	≥1	5
(1) Arc/trolley occultor errors: Type 2 (A time out occurs before occultor reaches specified position)	< 10%	≥10%	5 - arc 6 - trolley	≥90%	6 - arc 7 - trolley
(1) Arc/trolley occultor errors: Type 1 (Occultor is not in specified position)	< 10%	≥10%	7 - arc 8 - trolley	≥90%	8 - arc 9 - trolley
(1) Neutral density filter errors	< 10%	≥10%	9	≥90%	10
(1) Spectral filter errors (Unable to put filter into specified position)	< 10%	≥10%	10	≥90%	11
(1) Exabyte error (unable to write to Exabyte)	---	≥10%	11	---	---
Nitrogen pressure in camera housing (psi)	5	≤2	12	---	12
No WWV (If the source of the time stamp on all images grabbed is not WWV, a yellow flag is set)	---	= # of images grabbed	13	---	---

(1) Error figure = (# of occurrences) ? images grabbed).

5.1.5 Dimension Variables

This section is not applicable to this instrument.

5.2 Annotated Examples

This section is not applicable to this instrument.

5.3 User Notes and Known Problems

ARM-TR-011.1, Whole Sky Imager Retrieval Guide. T.P. Tooman, November 2003.

5.4 Frequently Asked Questions

Hardware

Why does the WSI need to use an imager?

Originally, for acquiring radiance distributions, we used scanning photometers. Whereas they provided excellent radiance distributions, the more demanding task of high-quality cloud detection requires more simultaneity in the data. The imager acquires measurements in all directions at once, so cloud motion presents little problem. By using a 512 by 512 imager, we essentially have nearly 250,000 calibrated radiometers staring at the sky simultaneously.

How did you decide to use the 16-bit charge-coupled device (CCD), as opposed to using film, a vidicon, video camera, or intensified CCD?

We used film fisheye systems in the 60s and 70s; however, they cannot be processed quickly, and the radiometric content of the data is severely degraded or lost. For measuring daylight skies only, we moved to a CEPEX integrated data system (CID)-based video camera in the 80s. This had the advantage over vidicons in that calibration and geometric positioning accuracy are maintained. (This is not true of all video cameras; however; it is very important that they have fixed gain, and electronic characteristics such that they can be well calibrated.) In moving to the day/night application, we determined that the video cameras we evaluated did not have the sensitivity we required. Likewise, intensified CID systems did not have sufficient stability and noise control for our application. We have been very happy with the performance of the slow-scan, low-noise 16-bit CCDs we are using.

What is the purpose of the occultor?

The occultor is used to shade the lens and dome, so we don't get stray light. Most photographers have at one time taken pictures looking toward the sun and seen the resulting artifacts in the image; the occultor prevents these artifacts by shading the lens.

Why is the occultor so big?

It is not sufficient to cover the ½ ° solar disk. It is necessary to shade the full physical extent of the lens and the dome. Because the solar rays are parallel, the shade must be at least as big as the dome, which is 7". To avoid obscuring too large a solid angle, we place it 24" from the dome. The actual solid angle obscured by the shade is less than 1% of the sky dome. At the TWP site, we will be using a larger shade, which is fixed in the N-S direction and moves only in the E-W direction; it will obscure 6% of the sky, but should be more reliable for a 6-month unattended operation.

Why do you need the occultor under moonlight?

The flux control is set to bring the radiance of the moonlit sky and clouds on scale. Under moonlight, the moon is as bright relative to the sky (in the absence of urban lights) as the sun is relative to the daylight sky.

Observed Images

The image appears round. What is the user looking at?

The center of the image is the zenith (overhead), and the edge of the circular image is the horizon. The view cannot be the same as looking down at a map, because the WSI is looking up. If you imagine lying on the ground looking up, with your toes to the north, you can imagine the view of the WSI: E is right, W is left, S is top, and N is bottom.

Why do you use 16 bits, if you can only display 8 bits?

An 8-bit image has only 256 grey levels, which means it has a limited radiometric resolution and/or range. By saving and using the original 16-bit data, data over a larger range and with a finer resolution are available to the numerical processing.

Can you see the whole sky?

Yes, because we underfill (rather than overfill) the chip so that the full optical image falls on the chip.

What can the WSI see under starlight? Is it really visible and not infrared (IR)?

We do use visible at night, although currently we open up the passband to roughly 400 - 900 nm. We can see the milky way, stars such as the stars in Orion's belt, clouds that are not visible to the human at night, and the light of distant cities. Often when the night visually appears clear, there are cirrus layers easily detectable by the sensor.

How does the sensor adjust to the changing light conditions?

The flux control algorithm embedded in the control software computes the solar zenith angle and the lunar zenith angle, phase angle, earth-to-moon distance, and resulting relative brightness. Using these values, the desired combination of filter and exposure selection is chosen. The imager has sufficient dynamic range within each image so that the system need not correct for variations in lighting conditions because of cloud cover to acquire onscale data.

Cloud Decision Images

How is cloud cover computed?

Please see cloud cover determination in Theory of Operations, Section 7.2. In general, an opaque cloud is defined as a cloud of a given whiteness (or measured red/blue ratio). A thin cloud is defined as a region that is whiter than the clear sky would be. In this process, an adjustment is made so that haze is normally not identified as thin cloud. The algorithm does a very nice job of detecting clouds, whether they are large or small (the resolution is about 17 m for a cloud at 3000 m, and 6 m for a cloud at 1000 m). It is not fooled by dark clouds, and it has no problem seeing high clouds. Sometimes thin clouds near the sun will be incorrectly labeled opaque clouds, and the choice of when to define an increasingly thick haze as a thin cloud is something that we hope to better define in the future.

6. Data Quality

6.1 Data Quality Health and Status

The following links go to current data quality health and status results.

DQ HandS (Data Quality Health and Status)
NCVweb for interactive data plotting using.

The tables and graphs shown contain the techniques used by the Atmospheric Radiation Measurement (ARM) Program's data quality analysts, instrument mentors, and site scientists to monitor and diagnose data quality.

6.2 Data Reviews by Instrument Mentor

- QC frequency: Limited
- QC delay: N/A
- QC type: N/A
- Inputs: WSI images
- Outputs: Not specified
- Reference: N/A.

At the present time, data quality control beyond inspection of images is very limited. A considerable effort might be required to compare cloud retrievals on a regular basis with the Belfort laser ceilometer (BLC), the Marine Physical Laboratory (MPL), or VCEIL data. A contract is being set up with Mission Research Corporation to produce night and thin cloud retrieval algorithms. Additionally, instrument mentor Tim Tooman is trying to develop a calibrated radiance retrieval.

6.3 Data Assessments by Site Scientist/Data Quality Office

All Data Quality (DQ) Office and most Site Scientist techniques for checking have been incorporated within DQ HandS and can be viewed there.

6.4 Value-Added Procedures and Quality Measurement Experiments

Many of the scientific needs of the ARM Program are met through the analysis and processing of existing data products into "value-added" products or VAPs. Despite extensive instrumentation deployed at the ARM sites, there will always be quantities of interest that are either impractical or impossible to measure directly or routinely. Physical models using ARM instrument data as inputs are implemented as VAPs and can help fill some of the unmet measurement needs of the program. Conversely, ARM produces some VAPs not to fill unmet measurement needs, but to improve the quality of existing measurements. In addition, when more than one measurement is available, ARM also produces "best estimate" VAPs. A special class of VAP, called a Quality Measurement Experiment (QME), does not output geophysical parameters of scientific interest. Rather, a QME adds value to the input datastreams by providing for continuous assessment of the quality of the input data based on internal consistency checks, comparisons between independent similar measurements, or comparisons between measurement with modeled results, and so forth. For more information, see the VAPs and QMEs web page.

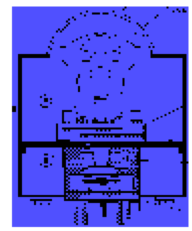
7. Instrument Details

7.1 Detailed Description

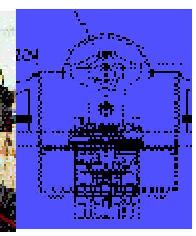
7.1.1 List of Components

The WSI is designed and built by Marine Physical Lab. The primary components of the system are listed below:

- Camera System:
  - Fisheye Lens - 180? field of view
  - Filter Changer with spectral and neutral density filter wheels
  - Shutter - electrically driven mechanical
  - Digital CCD Camera - Photometrics 16 bit with fiber-optic taper
  - Purged Camera Housing to enclose above items.

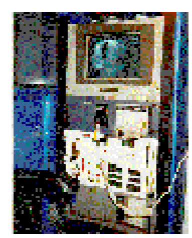


- Automatic Solar/Lunar Occultor:
  - Arc with Arc Drive (along East-West axis)
  - Trolley and Trolley Drive (along North-South axis)
  - Sunshade and 4-log neutral density filter.



- Environmental Housing:
  - Weatherproof housing to enclose camera system and the following items:
  - Thermo-electric Air Cooler
  - Temperature Controller
  - Liquid Coolant system with Flow Meter and Flow Switch
  - Relative Humidity Sensor.

- Controller:
  - Sensor Accessory Control Panel
  - Occultor Accessory Control Panel
  - Field Hardened PC Computer (486) and boards
  - Monitor
  - 8 mm Tape Drives
  - External accurate clock
  - Field Hardened Computer Rack to enclose the above items.



7.1.2 System Configuration and Measurement Methods

The WSI consists of the sensor unit and the controller. The sensor unit includes the optical system with a solid-state CCD camera and a filter changer, the solar/lunar occultor, and environmental protection

The radiance images are acquired through a Nikkor 8mm, f/2.8 fisheye lens. The lens 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.

For the WSI to acquire images under all possible lighting conditions (sunlight, moonlight, and starlight), it must be able to handle an approximately 9-decade range of lighting. To help accomplish this, a neutral density (ND) filter wheel containing 2- and 3-log ND filters is positioned between the lens and CCD imaging chip. The spectral filter wheel containing the red (650-nm) and blue (450-nm) filters is also positioned between the lens and CCD chip.

The imaging camera is a Photometrics Slow Scan CCD. This camera generates very low noise, has outstanding sensitivity characteristics, and produces a high quality image. Its 16-bit digitization (approximately 4-log range) allows for fine radiometric resolution.

To prevent direct sunlight or moonlight from hitting the protective dome covering the lens and producing artifacts in the image from scattering, a solar/lunar occultor is actively positioned between the sun/moon and dome. The occultor has drive controls for 2 degrees of freedom and is automatically positioned in the correct place by the controlling computer. The central portion of the occultor contains a 4-log ND filter that allows detection of the sun and moon.

A modified solar/lunar occultor has been designed for deployment to some locations. The modified design has 1 degree of freedom; that is, the trolley is replaced with a fixed shade. The width of the fixed shade is the same as the diameter of the shade on the trolley design, and the length of the shade is determined by site requirements. For the Surface Heat Budget of the Arctic Ocean (SHEBA) and NSA sites, the shade will cover the full 180 degrees to allow blockage of the sun as it moves around the horizon. For the TWP sites, the shade will extend from about +23° to -23°. The arc drive for the modified occultor design is the same as for the original design. The ND filter is not present in the modified design.

Special Data Collection Processing (IDCP Information)

The attached file lists all the file names for the WSI instrument data products.

7.1.3 Specifications

This section lists physical parameters describing the WSI. Some measured characteristics may vary slightly.

Physical Characteristics:

- Sensor Dimensions: 28" W x 36" D x 36" H
- Sensor Weight: 410 lb
- Sensor Power: 614 watts (79 must be on UPS)
- Controller Dimensions: 26" W x 26" D x 52" H
- Controller Weight: 450 lb
- Controller Power: 150 watts (must be on UPS).

Optical Characteristics:

- Spectral Filters at 450 nm and 650 nm and open hole
- Spectral passband width: 70 nm
- Neutral Density Filters at 0, 2, and 3 logs (decades) neutral density
- Fisheye-Nikkor 8mm f/2.8 lens
- Angular resolution: 1/3°
- Field of view 180 degrees (typically 181?)
- CCD: Thomson TH7895B, Grade 1
- 512 x 512 pixels
- 16 bit A/D readout at 40,000 pixels/second
- 25 mm to 11 mm fiber optic reducer.

Thermal Characteristics:

- CCD cooled to -35?C via 3-stage Peltier and liquid water/alcohol coolant
- Environmental Housing held at 60°F via thermo-electric air cooler
- Camera electronics (including A/D and pre-amp) help to 60°F.

Calibration Characteristics:

- Measures all sky conditions, including full sun to starlight
- Dynamic Range (overall): 10.6 log or 40000000000:1
- Dynamic Range (single image): 45800:1
- Readout Noise: 1.6 counts out of 65,536 grey levels
- Uniformity (Spatial Variation): 1.6% (correctable)
- Precision (Temporal Variation): 0.2%
- Nonlinearity: <= 1% up to signal 10k, <= 3% up to signal 50k (correctable)
- Pixel Resolution: 0.36?
- Avg. Deviation from Equi-Distant: 1.2? (correctable).

Control Characteristics:

- Image Exposure Time: Variable, 100 msec day, 1 min starlight
- Automated Exposure Adjustment based on solar/lunar conditions
- Solar/Lunar Occultor to shade lens and optical dome
- Automated Occultor Position based on solar/lunar position
- Self-checks for proper readouts and data acquisition
- Automated self-shutdown under pre-defined conditions
- Automated recovery from power down when power returns.

7.2 Theory of Operation

The WSI is designed to run either autonomously or networked to a site data system. It runs 24 hours a day, acquiring images at user-specified intervals. For the ARM Program, this interval is normally 10 minutes. For other applications, acquisition of image sets as often as once a minute is possible.

The system performs its own housekeeping, which includes positioning the solar/lunar occultor, acquiring the image set, saving data to tape drive for archival and to hard disk for network access, processing the data to yield cloud cover, and performing self-checks. To complete these steps, the system is able to determine the solar or lunar position (given the correct input location). Also, the WSI includes a flux control algorithm, which checks sun location, moon location, phase, and earth-moon distance; from these parameters the ND filter and exposure to use are determined.

When data are acquired, the first step is to display an image for the user. The raw data are 16 bit, (i.e., have a grey scale range of 0 - 65,535). To view the data, it is necessary to determine the portion of the range occupied by the data (such as grey levels 1000 - 8000) and map this into the 8-bit image (256 grey levels) used to display an image. The WSI includes an automated windowing algorithm, which determines a reasonable range to display, and derives the 8-bit image and displays it. (The 16-bit raw data are also always retained in unmodified format for further use.)

Once the raw data have been saved, and the windowed image displayed, the WSI proceeds with the cloud decision algorithm (unless this option is turned off). This algorithm first applies calibration factors to the 16-bit data, then ratios the red and blue images to provide a ratio image. As a first step, the ratios are thresholded to identify the opaque clouds. Thus, opaque clouds are identified by their spectral character.

In addition, a library of clear-sky ratio images for a full range of solar zenith angles must be stored in advance. This library is site-dependent, because it depends on such factors as site altitude (thus it can only be determined after the imager has been at the site for a reasonable period). This library is used to determine the background clear-sky ratio for a given solar zenith angle, which is then adjusted to compensate for variations in the aerosol load. The ratio image being analyzed is then compared with this background ratio on a pixel-by-pixel basis. The algorithm identifies a pixel as thin cloud if the test image ratio exceeds the background ratio by 20%. Thus, a pixel is identified as thin if its spectral ratio is not as high as that of an opaque cloud, but is significantly higher than that of the clear sky at the same look angle and solar/lunar angle.

If the aerosol load is so high (i.e., the sky is so hazy) that the clear-sky ratio exceeds the opaque ratio in any pixels, then these pixels may be labeled indeterminate. For example, on a very hazy day, the aureole may be labeled indeterminate. Once the full image has been processed, the cloud cover may be determined by evaluating the number of pixels inside the image, which are labeled opaque or thin cloud. (Normally no correction for the solid angle per pixel is required, as this introduces very small changes in the total result.)

The algorithm also labels pixels that are offscale bright or dark, and in the future it will label pixels that are blocked by the occultor. The current interactive cloud decision algorithm identifies both opaque and thin clouds; however, the near-real-time version of the algorithm fielded with the instruments only presents the opaque cloud results at this time. The extension of the thin cloud algorithm for near-real time use will be under development in the near future.

From the cloud decision images, in which each pixel is identified as opaque cloud or no cloud, the cloud cover over the full sky is computed, as well as the cloud cover in nine sectors: a 10-degree circle at the zenith, four quadrants running from 0 to 45° zenith angle, and four quadrants running from 45 to 90° zenith angle. In addition, other cloud products, such as cloud path length, area, and perimeters, will be computed at the Experiment Center. (See Value-Added Procedures and Quality Measurement Experiments, Section 6.4, for details and Data Descriptions and Examples, Section 5, for sample plots).

These cloud product results may be used for evaluation of the nature of the cloud heterogeneities, their impact on radiative transfer models, and the impact of the cloud cover on the surface fluxes. The zenith measurements may be used to evaluate zenith -ooking instruments.

An additional product is the sky radiance distribution. When each image is calibrated for absolute radiance, the image consists of more than 200,000 measurements of sky radiance acquired simultaneously at 1/3° spatial resolution. This product can be used in several ways: evaluation of the clear-sky radiance distributions, potentially including extraction of aerosol characteristics, evaluation of the cloud radiances and their relations to heterogeneities, evaluation of the variations in the diffuse irradiance (which can be computed from the radiances), evaluations of the solar disk for potential determination of optical depth and direct irradiance, and evaluation of the fine-scale temporal and spatial variations in these quantities.

Finally, a third product that should be of use to the science team is a visual presentation of the images. Because the data can be presented as visual images (like pictures), they present tremendous information to the trained observer. One can qualitatively evaluate cloud type and opacity, and the general character of the cloud field. Cloud time lapse loops are often particularly interesting and beautiful, and useful for qualitative evaluations of cloud motion and cloud cover persistence. Cloud loops are an easy tool for evaluating features such as orographic clouds that may affect the net flux, and yet not be detected by the zenith-looking sensors.

Potential future developments include use of the instruments for sub-visual cirrus detection, 3-D retrievals, and cloud typing. At this time, two instruments are fielded, and more emphasis is being placed on transfer of the analysis techniques from the vendor to the experiment center to enable fast data transfer to the science team.

7.3 Calibration

7.3.1 Theory

Presently, calibration occurs at Marine Physical Lab prior to fielding the instruments. These calibrations are done quite rigorously, so that the limiting accuracy should be the accuracy of the calibration sources. Some of the calibrations perform the primary function of testing whether system performance is up to the quality standard demanded by the nature of the sensing task.

Long-term maintenance of the calibrations will probably depend on the extent to which the absolute radiance distributions are utilized. It is envisioned that a field calibration device will be important for this application. For the application of determining cloud cover, the calibration stability is less critical, because the system uses image ratios, and only relative calibration must be stable or corrected for. The most critical calibration, the dark calibration, is measured in the field as part of the automated data acquisition procedure. The development of a field calibration device is recommended to ensure long-term results.

The following sections give a brief overview of the types of calibrations normally acquired for a WSI. Most of these calibrations are acquired in a calibration facility at MPL with a 2-meter precision calibration bar. The source is a 1000W FEL lamp traceable to the National Institute of Standards and Technology (NIST). A lambertian reflectance plaque is placed at the 0 point on the bar, and the imager views this plaque. A high-accuracy resistance shunt is used to monitor the lamp current, and the power supply automatically adjusts the voltage to maintain fixed current.

Dark Level vs. Exposure

A dark image is an image acquired with the shutter closed, and provides a measure of the dark current, electronic bias, and readout noise. The dark current is pixel-dependent, and is normally subtracted from the measured images in the field. In the lab, the dark image is acquired as a function of shutter exposure to characterize camera performance. In the field, a dark image is acquired whenever the exposure changes, so that a current dark image may be subtracted in the near-real-time processing in the field.

Dark Level Repeats

Ten to 20 repeat dark images are acquired at each of two exposures to characterize the spatial vs. temporal variance in the dark images.

Exposure Calibration - Short Exposures

Images of the uniform lambertian reflectance plaque are acquired at short exposure times ranging from 15 msec to 1000 msec to measure the effective shutter opening time.

Exposure Calibration - Long Exposures

Images are acquired at longer exposure times ranging from 15 msec to 3 minutes to verify system linearity as a function of input exposure time.

Radiometric Linearity

In this calibration, the distance between the calibration lamp and the reflectance plaque are varied by known amounts on the precision bar, so that the radiance presented to the sensor may be varied by known amounts. This calibration is used to determine whether the sensor response is linearly related to the radiance, and measure the non-linearities, if any, so that the data may be corrected for linearity.

Precision and Uniformity

Twenty images of the reflectance plaque are gathered in quick succession. From these images, a variety of spatial and temporal statistics are determined. These are used to characterize the precision (temporal variance) and the uniformity (spatial, i.e. pixel-to-pixel) variance.

Filter Passband Calibrations

To provide absolute radiance, it is necessary to know the effective lamp irradiance over the passband of the instrument. To determine this, it is necessary to know the lamp output as a function of wavelength, the CCD sensitivity as a function of wavelength, and the transmittance of each filter as a function of wavelength. Lamp and CCD calibrations are provided by the vendors, and the filter passband calibrations are measured separately.

Absolute Radiance Calibrations

Absolute calibrations are acquired at a fixed ND filter setting, in each spectral filter. In each spectral filter, measurements are acquired at each of five lamp positions, and then repeated. The 5 lamp positions yield five signals for five different radiances. If non-linearities have been corrected for properly, these five measurements should yield the same calibration constant, in the absence of stray light or other measurement error. The redundancy in this procedure yields a more accurate determination of the calibration constant, and also enables an evaluation of calibration uncertainty (this uncertainty is less than 0.5%). This calibration is performed for each combination of spectral and neutral density filter.

Aperture Calibration

This calibration characterizes the variation in the overall sensitivity as a function of aperture setting.

Rolloff Calibration

The rolloff calibration characterizes the variance in overall sensitivity as a function of look angle or angle with respect to the lens normal. This calibration is acquired using a rotary table to accurately vary the look angle of the lens, while holding the position of the lens with respect to the plaque fixed. Measurements are acquired for each spectral band.

Flat Field Calibration

The flat field calibration is a measure of the variation in pixel sensitivity at each pixel over the whole image. This correction is not required for cloud decision results or image viewing, but is required for the absolute radiance distribution extraction. Together, the dark image and the flat field image may be used to adjust the pixel-to-pixel variations in bias and gain. The WSI presents special difficulty in flat fielding, as a result of some of the characteristics of the fiber-optic taper. A unique technique was developed using a 1-meter integrating sphere, and using numerical corrections to remove certain artifacts of the sphere.

Geometric Calibration

The spatial relationship between zenith angle in object space and pixel position in image space is measured in this calibration. Whereas this relationship is nearly linear, it is MPL's practice to characterize the relationship, and correct for the non-linearity.

7.3.2 Procedures

7.3.3 History

Calibration for WSI01 occurred in September through November 94, with additional calibrations in December 94 and March 95. Calibrations for WSI02 occurred in August 95. As of March 96, not all of these have yet been evaluated, but results to date are excellent. For example, the self-consistency of the absolute calibrations was found to be within 0.5% or better. Some of the calibration results are listed in the WSI characteristics discussion.

7.4 Operation and Maintenance

7.4.1 User Manual

This section is not applicable to this instrument.

7.4.2 Routine and Corrective Maintenance Documentation

This section is not applicable to this instrument.

7.4.3 Software Documentation

ARM-TR-011.1, Whole Sky Imager Retrieval Guide. T.P. Tooman, November 2003.

7.4.4 Additional Documentation

See the SGP Preventative Maintenance Procedures.

7.5 Glossary

See the ARM Glossary.

7.6 Acronyms

AdaM ARCS Data Management
ARCS Atmospheric Radiation and Cloud Stations
ARM Atmospheric Radiation Measurement (Program)
CCD charge-coupled device
CID CEPEX integrated data system
DQ Data Quality
IR infrared
MPL Marine Physical Laboratory
ND neutral density
NIST National Institute of Standards and Technology
NSA North Slope of Alaska
QC quality control

QME	Quality Measurement Experiment
SDS	site data system
SGP	Southern Great Plains
SHEBA	Surface Heat Budget of the Arctic Ocean
TWP	Tropical Western Pacific
VAP	value-added product
WSI	Whole-Sky Imager

Also see the ARM Acronyms and Abbreviations.

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