DOE/SC-ARM-TR-178

Shortwave Array Spectroradiometer–Zenith Instrument Handbook

CJ Flynn

April 2016

DISCLAIMER

DOE/SC-ARM-TR-178

Shortwave Array Spectroradiometer–Zenith Instrument Handbook

CJ Flynn, Pacific Northwest National Laboratory

April 2016

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

AOD	aerosol optical depth
ARM	Atmospheric Radiation Measurement Climate Research Facility
ARRA	American Recovery and Reinvestment Act
ASCII	American Standard Code for Information Interchange
CCD	charge-coupled device
CWV	column water vapor
DOE	U.S. Department of Energy
F	Fahrenheit
FWHM	Full Width at Half Maximum
GPCI	GEWEX/WGNE Pacific Cross-section Intercomparison
GSFC	Goddard Space Flight Center (NASA)
Hz	hertz
IOP	intensive operational period
MAGIC	Marine ARM GPCI Investigation of Clouds
MS	Microsoft Corporation
NASA	National Aeronautics and Space Administration
NIR	near infrared
NIST	National Institute of Standards and Technology
nm	nanometer
QC	quality control
QME	Quality Measurement Experiment
RH	relative humidity
RSS	Rotating Shadowband Spectroradiometer
SASHe	Shortwave Array Spectroradiometer–Hemispheric
SASZe	Shortwave Array Spectroradiometer–Zenith
SGP	Southern Great Plains, an ARM megasite
USB	Universal Serial Bus
UT	Universal Time
UTC	Coordinated Universal Time
UV	ultraviolet
VAP	Value-Added Product
VIS	visible

Contents

Acronyms and Abbreviations iii
1.0 General Overview 1
2.0 Contacts 2
2.1 Mentor 2
2.2 Instrument Developer 2
3.0 Deployment Locations and History 2
4.0 Near-Real-Time Data Plots 3
5.0 Data Description and Examples 4
5.1 Data File Contents 4
5.1.1 Primary Variables 5
5.1.2 Secondary/Underlying Variables 5
5.1.3 Diagnostic Variables 5
5.1.4 Data Quality Flags 5
5.1.5 Dimension Variables 5
5.2 Annotated Examples 5
5.3 User Notes and Known Problems 7
6.0 Data Quality 7
6.1 Data Quality Health and Status 7
6.2 Value-Added Procedures and Quality Measurement Experiments 7
7.0 Instrument Details 7
7.1 Detailed Description 7
7.1.1 List of Components 9
7.1.2 Specifications 9
7.2 Theory of Operation 10
7.3 Calibration 10
7.3.1 Theory 10
7.4 Operation and Maintenance 12
7.4.1 Installation and Operation Procedures 12
7.4.2 Routine and Corrective Maintenance Documentation 13
7.4.3 Additional Documentation 13
7.5 Glossary 13
7.6 Acronyms 13

Figures

1. SASZe and monitor in the “darkroom” at SGP. 1
2. Zenith transmittances from SGP SASZe filterbands for Sept 27, 2015. 4
3. Zenith radiance spectra from SASZe #2 at PVC, Jan 28, 2013. 6
4. Time series of SASZe and Cimel zenith radiance at PVC February 1, 2013. 7
5. SAS instrument layout concept. 8
6. Initial SASZe Sky Collector “SASZe-a”. 9
7. Example of spectrometer internal stray light measurement. 12
8. Polarization sensitivity of SASZe collector “type b” to 100% linearly polarized light. 12

Tables

1. Deployment and calibration of SASZe1. 3
2. Deployment and calibration of SASZe2. 3

1.0 General Overview

The Shortwave Array Spectroradiometer – Zenith (SASZe) provides measurements of zenith spectral shortwave radiance at 1Hz over a continuous spectral range from approximately 300 nm to 1700 nm. The SASZe design connects an optical collector located outdoors to a pair of spectrometers and data collections system located indoors within a climate-controlled building via an umbilical cable of fiber optic and electrical cables. The light collector incorporates a collimator yielding a 1-degree Full Width at Half Maximum (FWHM) field of view. The data-acquisition electronics and spectrometers include an in-line fiber optic shutter and two Avantes fiber-coupled grating spectroradiometers within a temperature-controlled container. The Avantes Avaspec ULS 2048 charge-coupled device (CCD) spectrometer covers the wavelength range from about 300-1100 nm with a pixel spacing of less than 0.6 nm and a spectral resolution of about 2.4 nm FWHM. The Avantes Avaspec NIR256-1.7 spectrometer covers the wavelength range from about 950 nm to 1700 nm with a pixel spacing of less than 4 nm and a spectral resolution of about 6 nm FWHM.

The SAS measurements can be used to:

- Retrieve cloud optical depth, particle size and cloud water path.
- Test the cloud optical depth retrieval for overcast and broken cloud fields.
- Validation/comparison with Southern Great Plains (SGP) site surface remote sensors and future cloud intensive operational period (IOP) campaigns.
- Multivariate analysis to derive information content in hyper spectral data sets and to improve cloud retrieval algorithm development.
- Compare with radiative transfer models for testing and validating retrieval procedures.

Figure 1. SASZe and monitor in the “darkroom” at SGP.

2.0 Contacts

2.1 Mentor

Connor J. Flynn
Pacific Northwest National Laboratory
902 Battelle Boulevard
P.O. Box 999, MSIN K4-28
AML Building Room 102
Richland, WA 99352 USA
Tel: 509-375-2041
Cell: 509-554-7791
Connor.Flynn@pnnl.gov

2.2 Instrument Developer

Connor J. Flynn
Pacific Northwest National Laboratory
902 Battelle Boulevard
P.O. Box 999, MSIN K4-28
AML Building Room 102
Richland, WA 99352 USA
Tel: 509-375-2041
Cell: 509-554-7791
Connor.Flynn@pnnl.gov

3.0 Deployment Locations and History

The SAS–Ze systems were produced with funding from the American Recovery and Reinvestment ACT (ARRA) and were delivered at the end of calendar year 2010. The initial installations were scheduled in 2011 to the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility SGP site in March and the first ARM Mobile Facility (AMF1) field campaign in Nainital, India in June. The system deployed to SGP is dubbed “SASZe #1”. The system deployed to the AMF1 is dubbed SASZe #2. The design for the optical collector was modified so there are now two distinct optical collector designs denoted as “a” and “b”. There are two chief differences. 1) The original design “a” incorporated motion control to fix the orientation of the collector and a shadowband with respect to solar position. The new design “b” eliminates active motion control and substitutes a long gershun “baffle tube” in place of the shadowband to eliminate direct sunlight. 2) The original design incorporated a crystal linear polarizer maintained at 45 degrees to solar azimuth to reduce sensitivity to the linear polarization of zenith sky radiance. The new design replaces the linear polarizer with two broadband depolarizers. The sky collector for SASZe1was replaced prior to shipboard deployment for the Marine ARM GPCI Investigation of Clouds (MAGIC) campaign. The sky collector for SASZe2 was replaced during calibration exercises in March 2013. Tables 1 and 2 list deployment, calibration, and modification timelines for SASZe1 and SASZe2, respectively.

Table 1. Deployment and calibration of SASZe1.

Begin Date	End Date	Serial No.	Location	Description
2011-03-22	2012-07-02	SAS-Ze1a	SGP C1	Initial installation
2012-05-18	2012-05-19	SAS-Ze1a	SGP C1	Calibrate with ARM 10" sphere
2012-07-03	2012-09-15	SAS-Ze1a	PNNL	Removed, prepare for MAG
2012-10-06	2013-01-07	SAS-Ze1b	AMF2, MAG	Deployed for MAG part 1
2013-03-14	2013-03-14	SAS-Ze1b	NASA GSFC	Calibrate with Grande
2013-05-06	2013-05-07	SAS-Ze1b	NASA Ames	Calibrate ARCHI (post-broken fiber)
2013-05-23	2013-09-25	SAS-Ze1b	AMF2, MAG	Deployed for MAG part 2
2013-11-20	2013-11-21	SAS-Ze1b	NASA Ames	Post-MAG/pre-SGP cals ARCHI
2013-12-20	2013-12-21	SAS-Ze1b	SGP C1	Post-shipping cals with 10" sphere
2013-12-21	2014-04-30	SAS-Ze1b	SGP C1	Redeployed, operational
2014-04-30	2014-05-02	SAS-Ze1b	SGP C1	Pre-shipping tests, cals 10" sphere
2014-05-13	2014-05-15	SAS-Ze1b	NASA GSFC	Calibration with Grande
2014-05-28	current	SAS-Zeb1	SGP C1	Redeployed, operational

Table 2. Deployment and calibration of SASZe2.

Begin Date	End Date	Serial No.	Location	Description
2011-07-21	2012-04-01	SAS-Ze2a	PGH	Initial installation
2012-06-27	2013-03-11	SAS-Ze2a	PVC	AMF1 TCAP I
2013-01-09	2013-01-09	SAS-Ze2a	NASA GSFC	Calibration with Grande
2013-01-13	2013-03-11	SAS-Ze2a	PVC	AMF1 TCAP I
2013-03-14	2013-03-14	SAS-Ze2a	NASA GSFC	Calibrate Ze2a with Grande
2013-03-14	2013-03-14	SAS-Ze2b	NASA GSFC	Calibrate Ze2b with Grande
2013-03-16	2013-07-10	SAS-Ze2b	PVC	AMF1 TCAP II
2013-07-25	2013-07-25	SAS-Ze2b	NASA GSFC	Damaged on return shipping
2013-09-06	2013-09-06	SAS-Ze2b	NASA Ames	Post-repair, pre-MAO cals with HISS
2013-12-11	current	SAS-Ze2b	MAO	AMF1 GoAmazon

4.0 Near-Real-Time Data Plots

Near-real-time plots of SASZe diagnostic and sky radiance data generated by the ARM Data Quality Office may be viewed via the Plot Browser. Select the site (SGP, PGH, PVC, MAO) and scroll down the list of datastreams to find xxxsasze (where xxx stands for the relevant site abbreviation above). Figure 1, for example, shows zenith transmittances for a day with mostly clear skies and only two or three isolated cloud episodes around 19:30 UT and 22:00 UT. The top panel shows selected wavelengths from the

VIS/UV Si CCD spectrometer while the lower panel shows selected wavelengths from the SWIR/NIR InGaAs array spectrometer.

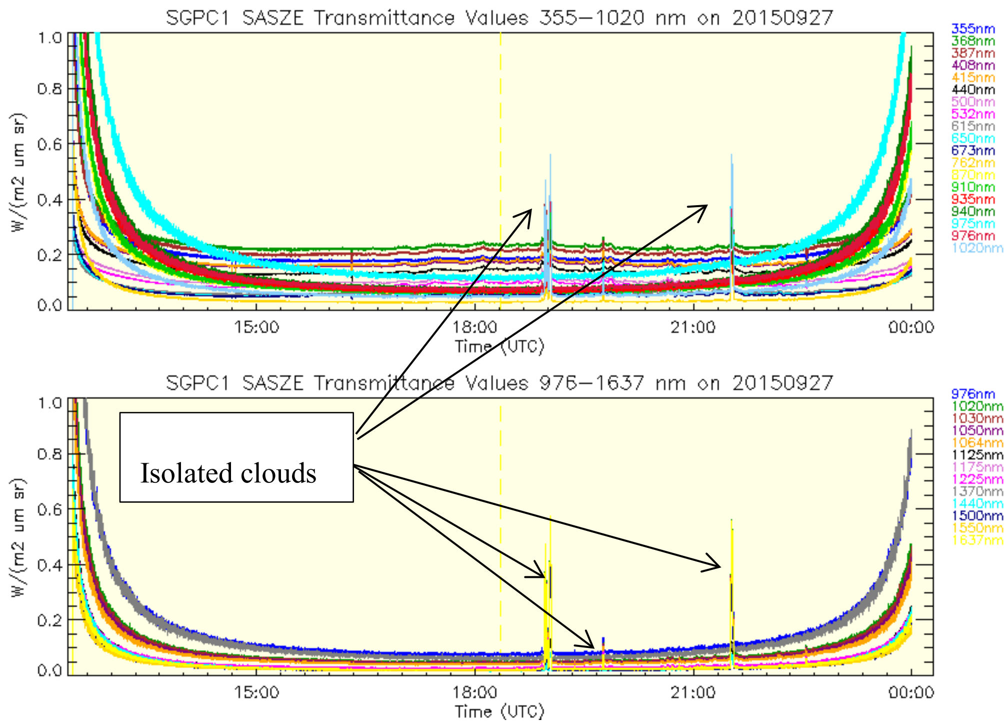

Figure 2. Zenith transmittances from SGP SASZe filterbands for Sept 27, 2015.

5.0 Data Description and Examples

5.1 Data File Contents

The SASZe data files are initially collected as "comma separated variable" American Standard Code for Information Interchange (ASCII) files of uncalibrated readings. The full content of the raw files is stored and available from the ARM Data Archive.

The raw ASCII files are then ingested into ARM netcdf as uncalibrated "a0" level files named as:

xxxsaszevisFN.a0.yyyymmdd.hhmmss.cdf : raw spectra from UV/VIS spectrometer
xxxsaszenirFN.a0.yyyymmdd.hhmmss.cdf : raw spectra from SWIR/NIR spectrometer

where yyyy ≡ year (i.e. 2006), mm ≡ month, dd ≡ day, hh ≡ hour, mm ≡ minutes, and ss ≡ seconds. The "vis" and "nir" files have identical structure. The field "spectra" contains raw uncalibrated readings from the grating spectrometers as digital "counts". The "vis" and "'nir" files each contain spectrometer-specific metadata including model and serial number, pixel wavelength mapping, integration times, and so on. Identical housekeeping measurements are duplicated in each file including shutter position, temperature and RH of various instrument elements, and computed solar ephemeris quantities.

The raw spectra are calibrated to units of $Wm^{-2}nm^{-1}sr^{-1}$ by subtracting background values (collected with shutter closed) and dividing by spectral responsivity and saved to a1-level netcdf data files named as follows:

xxxsaszevisFN.a1.yyyymmdd.hhmmss.cdf : calibrated radiance from UV/VIS spectrometer
xxxsaszenirFN.a1.yyyymmdd.hhmmss.cdf : calibrated radiance from SWIR/NIR spectrometer
xxxsaszefilterbandsFN.a1.yyyymmdd.hhmmss.cdf : calibrated radiance for wavelengths corresponding to other ARM filter measurements or having atmospheric relevance.

To avoid confusion with the uncalibrated "spectra" in the a0-level files, the calibrated radiance quantities are stored under the variable name "zenith_radiance" and reported in units of W/(m^2 um sr).

5.1.1 Primary Variables

The saszevis.a1 and saszenir.a1 datastreams report "zenith_radiance" in units of W/(m^2 um sr) as primary measurements. The saszefilterbands.a1 file reports both "zenith_radiance" and the unitless quantity "zenith_transmittance" at 31 selected wavelengths as primary measurements.

5.1.1.1 Definition of Uncertainty

The SASZe systems are calibrated annually using integrating spheres at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) or at NASA Ames that have been calibrated according to National Institute of Standards and Technology (NIST) standards. The absolute accuracy of the spectral radiance of these reference standards is typically between 1-3% depending on wavelength. The absolute accuracy for the SASZe can be no better than the calibration of the reference spheres, and in practice differences between similarly calibrated radiometers have been observed to be as large as 10%. These discrepancies are a topic of current research, but it is evident that the uncertainty in the absolute radiance calibration is not the dominate term. See the more detailed discussion under section 7.3.

5.1.2 Secondary/Underlying Variables

Solar ephemeris quantities (solar elevation, solar azimuth, airmass) are computed according to the geographic location and time in UTC.

5.1.3 Diagnostic Variables

The SASZe systems record a number of housekeeping parameters including the temperature and RH of the collector (near ambient conditions), the data acquisition equipment (located indoors), and the spectrometers (located inside a chilled refrigerator fed with dry air); local atmospheric pressure; and the tilt of the sky collector with respect to level. These are variables that monitor the health of the SASZe.

5.1.4 Data Quality Flags

Not available for this instrument at this time.

5.1.5 Dimension Variables

The hyperspectral SASZe "vis" and "nir" data files contain time and wavelength dimensions, while the "filterbands" data files contain only a time dimension.

5.2 Annotated Examples

Figure 2 below shows an example of clear-sky zenith radiance spectra from the SASZe VIS and NIR a1-level netcdf files collected from the SASZe2 at the AMF1 January 28, 2013. The blue line is the zenith radiance reported from the UV/VIS Si CCD spectrometer, while the red line is from the SWIR/NIR InGaAs array spectrometer. These spectrometers are independently calibrated from the same reference light source, so the agreement in the overlapping region illustrates the calibration accuracy while the disagreement at around 1000 nm is due mainly to signal-to-noise limitations of the UV/VIS spectrometer.

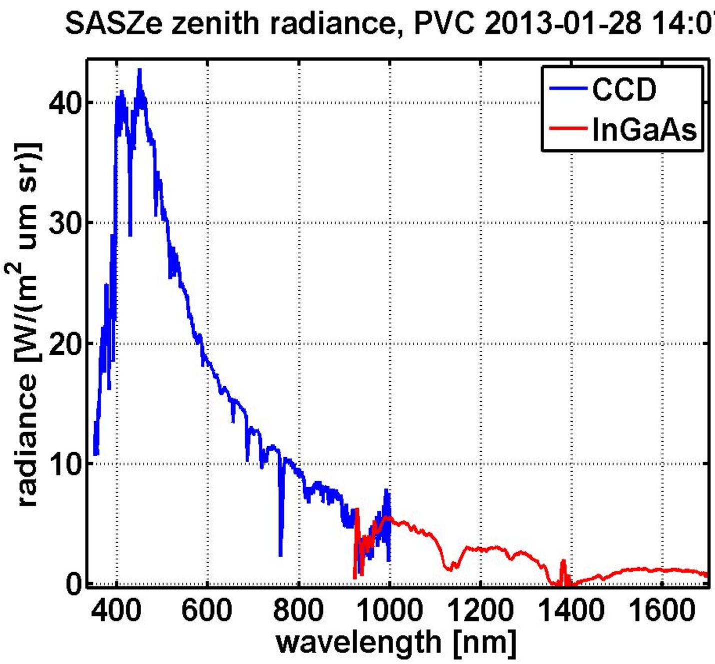

Figure 3. Zenith radiance spectra from SASZe #2 at PVC, Jan 28, 2013.

Figure 3 shows a time-series comparison of zenith radiances from the SASZe #2 and Cimel sun photometer (in cloud mode) at PVC for February 1, 2013. The SASZe measurements are displayed as very small dots but appear as a nearly continuous line since they are reported at 1 Hz. The Cimel cloud-mode data are less frequent and appear sporadically as small empty circles. The demonstrated agreement is at acceptable levels of several percent or less.

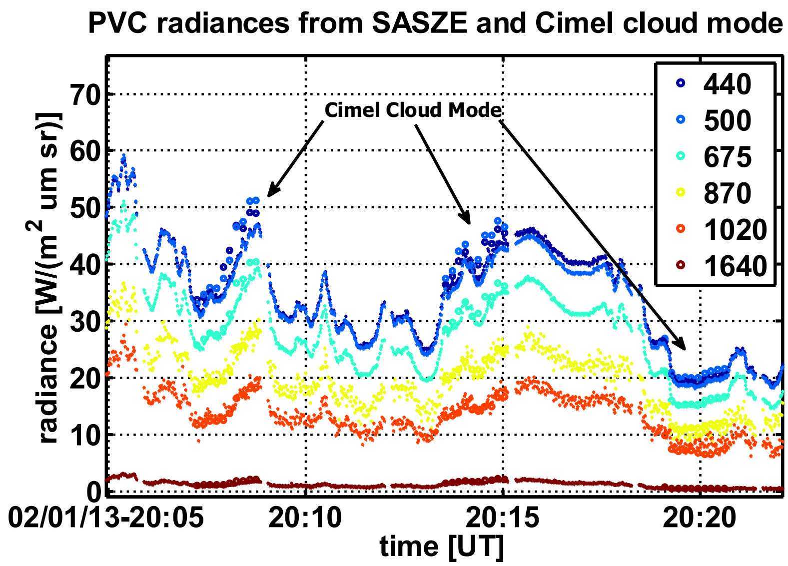

Figure 4. Time series of SASZe and Cimel zenith radiance at PVC February 1, 2013.

5.3 User Notes and Known Problems

Despite the quoted accuracy of the calibration sources on which the SASZe relies for absolute calibration of 1-2%, we have been unable to demonstrate agreement to this level when comparing to similarly calibrated instruments measuring zenith radiance (SWS and Cimel sky channels at SGP. NFOV2, Cimel sky channels, and SSFR for AMF1 and AMF2 MAGIC deployments). The reasons are not yet well understood.

6.0 Data Quality

6.1 Data Quality Health and Status

Data Quality for the SASZe will be available from the following web site maintained by DQ Hands: http://dq.arm.gov/

6.2 Value-Added Procedures and Quality Measurement Experiments

There are currently no Value-Added Products (VAPs) or Quality Measurement Experiments (QMEs) with the SASZe.

7.0 Instrument Details

7.1 Detailed Description

The SASZe and the related SASHe instruments share numerous design elements as listed in Figure 4. The sky collection optics of the SASZe are built around a fiber-coupled off-axis collimator oriented to view the zenith sky. The initial configuration of the SASZe (type “a”) shown in Figure 5 below included motion control and a shadowband to prevent direct sunlight exposure of the fore optics. The current SASZe collector (type “b”) no longer has motion control and instead relies on a passive 18” Gershun “baffle” tube to prevent exposure to direct sunlight unless the sun is very close to the zenith position. The current SASZe collector also includes two OFR DPU-15 uncoated broadband depolarizers in series to reduce polarization sensitivity to a few percent with 100% polarized light. The optical collector includes active heat control with Minco heating tape, and is vented with dry air to prevent condensation on optical surfaces. An umbilical containing a fiber optic and electrical cables connects the sky collection optics to rack-mounted data acquisition equipment and fiber-coupled spectrometers located inside a climate-controlled building. The spectrometers themselves are housed within a small refrigerator thermostatically controlled to +/- 1°F and supplied with dry air to keep relative humidity inside the refrigerator well below condensing levels.

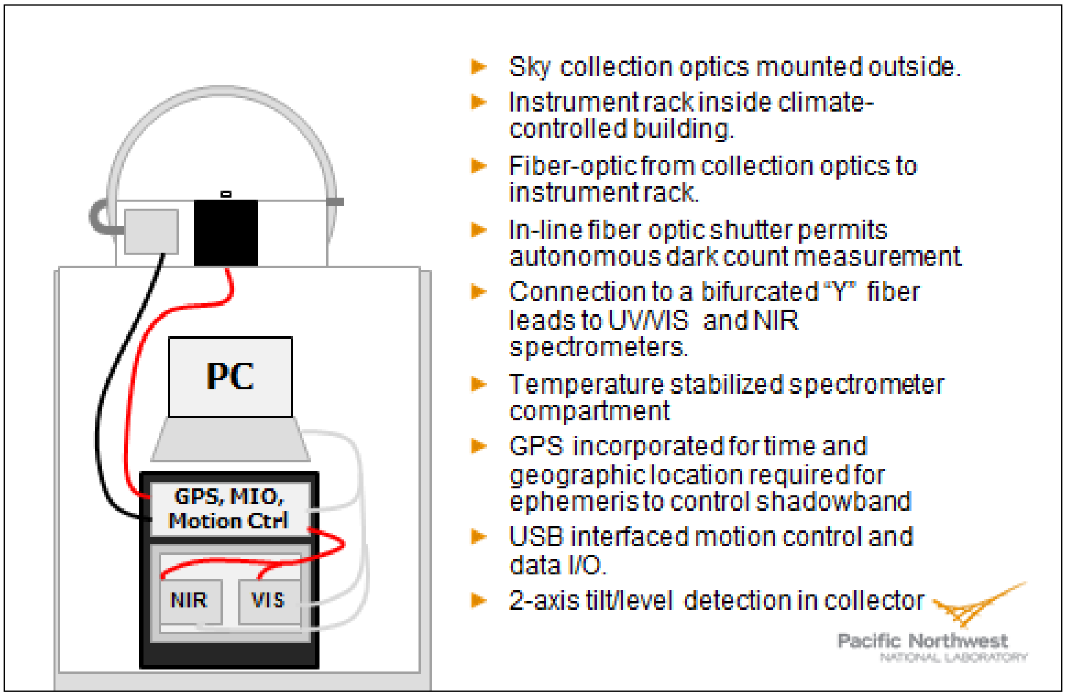

Figure 5. SAS instrument layout concept.

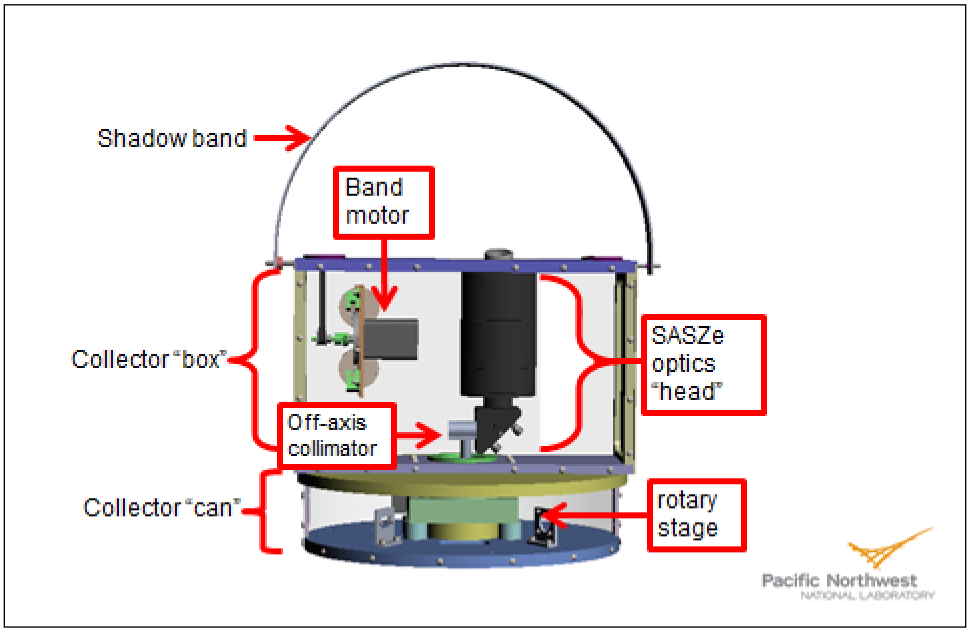

Figure 6. Initial SASZe Sky Collector "SASZe-a".

7.1.1 List of Components

- Thorlabs RC08FC narrow field of view (1° FWHM)
- Low OH silica fiber, 600 um core for transmission from 350-2500 nm
- Avantes FOS-1 inline fiber optic shutter
- FONT custom fiber optics Y-splitter 600 um to two 300 micron arms
- Spectrometers:
- Avantes Avaspec ULS 2048 CCD Si array
- Avantes Avaspec NIR256-1.7 linear InGaAs array
- A laptop running the latest Windows operating system. (Initially Microsoft WinXP, currently MS Windows 7)
- NiDAQ for analog/digital conversion and measurement control
- A USB interface between the computer and the spectrometers

7.1.2 Specifications

Wavelengths Measured:
2048 channels Si (300-1100 nm)
256 channels for the InGaAs (900-2200 nm).

Instrument Field of View: The field of view of the instrument is 1° FWHM.

Sampling Interval: Measurements are made at the rate of one per second during the day. The SASZe does not collect data before sunrise or after sunset.

Integration Time: The integration times for each spectrometer are adjusted by site and over the course of the year to approach the spectrometer dynamic range while avoiding saturation by bright cloud. However, irrespective of the specific integration times used, the data acquisition software averages as many individual spectra as possible within a given 1-second interval.

7.2 Theory of Operation

Photons incident on the collimator at the fore optics of the light collector travel through the large, single-core optical fiber through the in-line shutter to a 50/50 bifurcated Y-fiber that diverts the signal equally to the VIS and NIR spectrometers. Within each spectrometer, the light is spectrally dispersed by a diffraction grating and focused onto a solid-state linear detector array. The array is then read by an electronic interface that passes the data to the computer via a USB connection. Dark signals are obtained periodically at the same integration time that was used to measure the intensity, by closing the in-line shutter.

7.3 Calibration

7.3.1 Theory

Several aspects of the SASZe require careful characterization and/or calibration.

1. Spectral registration, mapping pixel number to wavelength. The vendor provides a pixel to wavelength mapping. We have confirmed the vendor pixel map is good to within a pixel using discharge lamps and discrete laser lines s references.
2. Spectral resolution. In addition to the pixel-to-wavelength mapping, the vendor also provides the spectral resolution for each spectrometer. We have nominally verified these vendor-supplied values based on the observed spectral shape of discrete line sources.
3. Internal stray light within the spectrometers. Figure 6 shows results from a measurement of internal spectrometer stray light determined by scanning a double-slit monochromator positioned in front of a broadband light source over the spectral range of the spectrometer. Except for a few isolated “hot pixels,” these results indicate stray light levels at or below 0.01% relative to the peak signal intensity. However, we have evidence suggesting stray light levels from broadband sources may approach 1% of measured spectra near the wavelength detection limits of either detector. We are evaluating potential corrections for this effect.
4. External stray light (for example, direct sunlight) scattered from the fore optics or leaking through fiber optic jacketing. By exposing and shading the collector under direct sunlight, we have confirmed that external stray light is at negligible levels compared to sky radiance counts.
5. Spectrometer signal linearity. By varying incident light levels and integration times we have documented the linearity for each grating spectrometer. The nonlinearity is less than 1% over most of our ambient light levels, and approaching 5% at the lowest intensity. These levels are small, though not negligible. We are evaluating corrections for robustness. These have not yet been incorporated in current processing.

6. Spectrometer temperature sensitivity. The CCD spectrometers show temperature response less than 0.1% per degree. The InGaAs spectrometers show higher temperature sensitivity, but this is mostly in thermal background levels that we address through frequent dark measurements. We have also identified that the InGaAs spectrometers show a trough in their temperature response so we operate our chiller centered on this minimum in temperature sensitivity rather than at the coldest temperatures that would yield the lowest darks.
7. Spectrometer polarization sensitivity. Gratign spectrometers and off-axis reflectors have intrinsic sensitivity to linear polarization orientation. We have measured the polarization sensitivity of the optical train end to end, and confirmed sensitivity to 100% polarized light at below 1% as shown in Figure 7 below.
8. Spectrometer spectral responsivity. The SASZe systems receive annual end-to-end radiance calibration by reference against integrating spheres at NASA Ames or NASA GSFC that have each been calibrated according to NIST standards. The absolute accuracy of the spectral radiance of these reference standards is typically between 1-2% depending on wavelength. The absolute accuracy for the SASZe can certainly be no better than the calibration of the reference spheres. However, in practice differences between similarly calibrated radiometers have been observed to be as large as 10%. These discrepancies are a topic of current research, but it is evident that the uncertainty in the absolute radiance calibration is not the dominate term.
9. Optical alignment. The SASZe type “b” currently deployed at ARM sites uses a long baffle tube to prevent exposure of fore optics to direct sun. It is possible for the optical alignment to drift such that the baffle tubes might occlude the instrument field of view. This would typically be expected to represent a slow systematic downward drift in measured radiance, but would also occur rapidly in response to severe weather and winds. It is currently not possible to detect this effect unambiguously, so this must be considered as a possible calibration uncertainty.
10. Optical surface conditions, soiling, condensation. The SASZe receives end-to-end calibration under laboratory conditions. However, it is operated under very different ambient conditions. Occasionally condensation has been observed under the exterior optical window–especially during MAGIC, and at SGP in 2011-12 before a dry air supply was provided to keep the optical surfaces free of condensation. As with mechanical misalignment, this effect is very difficult to detect unambiguously from the data, so it must be considered as an additional calibration uncertainty.

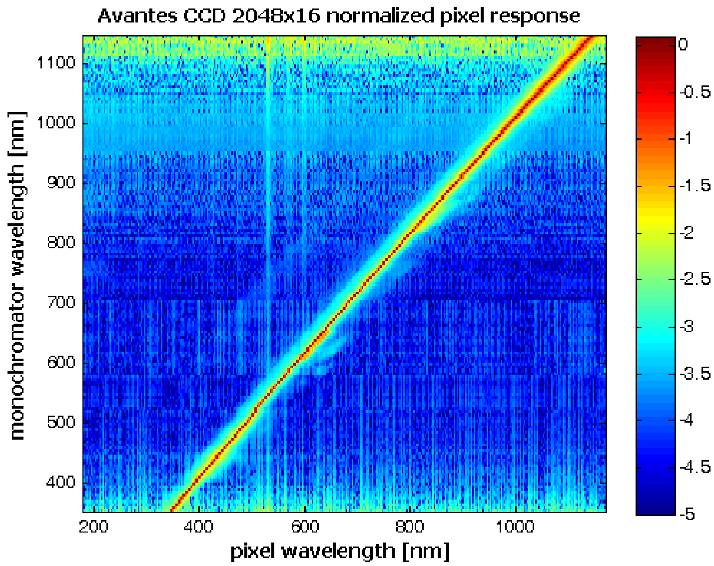

Figure 7. Example of spectrometer internal stray light measurement. The horizontal axis is the wavelength reported by the grating spectrometer. The vertical axis is the source wavelength provided by the scanning monochromator. The color scale is log-base 10, so a value of -3 on the color map corresponds to 0.1% stray light compared to the peak intensity normalized to one (the red diagonal line).

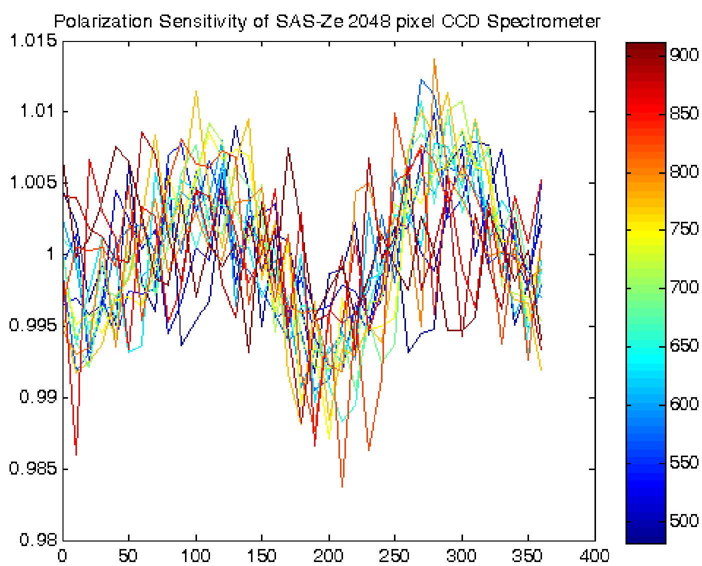

Figure 8. Polarization sensitivity of SASZe collector “type b” to 100% linearly polarized light.

7.4 Operation and Maintenance

7.4.1 Installation and Operation Procedures

Once installed by the mentor, the SASZe system is designed for autonomous operation. When the system is provided with power, the computer will auto start and will automatically begin to collect spectra according to defined schedules. The system requires daily cleaning of optical surfaces. In addition, it requires a supply of desiccant and/or dry air to keep optical surfaces free of condensation. A robust network connection is important as is a reliable time server in order to compute accurate solar ephemeris data.

Several documents have been prepared and provided for installation and operation of the SAS-Ze:

- Leveling and alignment of the SAS Instrument.docx
- Adjusting Band Physical Limits.docx
- FlexCouplerReplacement_figures.pptx
- Replacing Band Motor.docx.

7.4.2 Routine and Corrective Maintenance Documentation

Daily, weekly, and monthly preventative maintenance procedures have been developed with onsite support staff. Mostly this entails routine inspection and cleaning of optical surfaces, confirmation of housekeeping measurements falling in nominal ranges, and confirmation of the action of the shutter and appearance of spectra.

7.4.3 Additional Documentation

None available for this instrument.

7.5 Glossary

See the ARM Glossary (http://www.arm.gov/about/glossary.stm)

7.6 Acronyms

See the ARM Acronyms and Abbreviations (http://www.arm.gov/about/acronyms.stm)

ARM

CLIMATE RESEARCH FACILITY

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science