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ARM Shortwave Spectral Radiometry Strategy Review Report

L Riihimaki
C Flynn
A McComiskey

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ARM

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Organizers
L Riihimaki, National Oceanic and Atmospheric Administration (NOAA)
C Flynn, University of Oklahoma
A McComiskey, Brookhaven National Laboratory (BNL)

Participants
C Chiu, Colorado State University
D Feldman, Lawrence Berkeley National Laboratory
J Gristey, NOAA
A Habte, National Renewable Energy Laboratory (NREL)
C Herrera, University of Colorado (UC)
G Hodges, NOAA
S Jones, Aerodyne Research, Inc.
E Kassianov, Pacific Northwest National Laboratory
B Kindel, UC
M Kutchenreiter, NREL
K Lantz, UC
SE LeBlanc, National Aeronautics and Space Administration (NASA)
D Lubin, Scripps Institution of Oceanography
A Marshak, NASA
J Michalsky, Cooperative Institute for Research in Environmental Science
D Stanitski, NOAA
S Schmidt, UC
H Scott, Aerodyne Research, Inc.
H Telg, UC
A Theisen, Argonne National Laboratory
R Wagener, BNL

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Executive Summary

A meeting of experts in shortwave (SW) spectral measurements was held in February 2019 to discuss the current state of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility instrumentation and the potential scientific impact of these measurements. Instrument mentors and users reported significant progress in hyperspectral measurement quality, with good-quality data sets now possible at several field campaigns and fixed sites. Ongoing filter-based measurement improvements, including addition of the 1.6-micron channel to the multifilter rotating shadowband radiometer (MFRSR) and lunar tracking mode of the Cimel sun photometers, were also lauded as exciting developments to improve retrievals of aerosol radiative properties and size distributions.

Group discussion focused primarily on two scientific applications of hyperspectral measurements that could provide ground-breaking advances with current measurements. First, SW spectral measurements have the potential to provide new constraints on cloud microphysical processes, particularly related to aerosol-cloud interactions, which are a key uncertainty in climate feedback and sensitivity. Examples were given in how SW spectral measurements are currently being used to better understand and model the feedback between cloud optical properties and ice and snow melt in high latitudes; provide quantitative constraints on accumulation and accretion processes in warm-cloud precipitation formation; and identify mixing regime at cloud edges and thereby separate aerosol-cloud impacts from cloud dynamics in broken cloud conditions. While filter-based measurements can provide constraints in some of these conditions in combination with other sensors, hyperspectral measurements have the potential to retrieve the needed cloud microphysical and optical properties in new environments such as giving more accurate effective radius retrievals, identifying thermodynamic phase, and more accurately and flexibly separating aerosol, surface albedo, and cloud optical properties in heterogeneous environments.

Second, the emerging understanding of how hyperspectral measurements provide inherent information about three-dimensional (3D) radiative effects has the potential to constrain and improve estimates of cloud and aerosol radiative effects in new complex environments such as broken cloud conditions and complex aerosol and cloud scenes such as aerosol layers above clouds. This exciting new area of research has the potential to produce new parameterizations to account for phenomena such as the inherent biases in plane parallel radiative transfer calculations of shallow cumulus conditions modeled by the LES ARM Symbiotic Simulation and Observation (LASSO) workflow.

For the most strategic future investment in advancing scientific knowledge from these measurements, the group's highest-priority recommendations (more details in Section 5) were:

1. Provide data epochs of good-quality hyperspectral measurements with consistent calibration from several campaigns to give the community a testbed for science applications and retrieval development.
2. Invest in cloud retrieval development from hyperspectral measurements based on new approaches that take advantage of slopes and shapes of the spectra and are less sensitive to absolute calibration. Providing an initial product based on methods in the literature would allow the broader atmospheric science community access to the potential of these measurements for process studies.

3. Update aerosol retrievals of optical properties and size distributions to better leverage multi-instrument synergies and filter-based instrument upgrades.
4. Promote the availability and maturity of ARM's SW spectral measurements through a *Bulletin of the American Meteorological Society* (*BAMS*) article to engage a wider community of researchers with this rich data set.

Acronyms and Abbreviations

3D	three-dimensional
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
AMF	ARM Mobile Facility
AOD	aerosol optical depth
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
ASY	asymmetry parameter
AWARE	ARM West Antarctic Radiation Experiment
BAECC	Biogenic Aerosols − Effects on Clouds and Climate
BAMS	*Bulletin of the American Meteorological Society*
BSRN	Baseline Surface Radiation Network
CAUSES	Clouds Above the United States and Errors at the Surface
CMIP5	Coupled Model Intercomparison Project 5th phase
CSPHOT	Cimel sunphotometer
DARF	direct aerosol radiative forcing
DOAS	differential optical absorption spectroscopy-
DOE	U.S. Department of Energy
ENA	Eastern North Atlantic
ESM	earth system model
FOV	field of view
FSC	fractional sky cover
HPN	hyperspectral pyranometer
IR	infrared
ISDAC	Indirect and Semi-Direct Aerosol Campaign
LASIC	Layered Atlantic Smoke Interactions with Clouds
LASSO	LES ARM Symbiotic Simulation and Observation
LES	large-eddy simulation
LW	longwave
MFR	multifilter radiometer
MFRSR	multifilter rotating shadowband radiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NFOV	narrow field of view
NIMFR	normal incidence multifilter radiometer
NIR	near infrared
NIST	National Institute of Standards and Technology

NSA	North Slope of Alaska
ORACLES	Observations of Aerosols above Clouds and their Interactions
PAR	photosynthetically active radiation
PI	principal investigator
RSS	rotating shadowband spectroradiometer
RT	radiative transfer
SAS	shortwave array spectroradiometer
SASHE	shortwave array spectroradiometer−hemispheric
SASZE	shortwave array spectroradiometer−zenith
SGP	Southern Great Plains
SPN	sunshine pyranometer
SSA	single-scattering albedo
SSFR	solar spectral flux radiometer
SW	shortwave
SWS	shortwave spectroradiometer
TCAP	Two-Column Aerosol Project
TSI	total sky imager
TWST	three-waveband spectrally agile technique
UV	ultraviolet
VAP	value-added product
WMO	World Meteorological Organization

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1.0 Introduction

Radiation measurements have been an integral part of the DOE ARM facility's mission since its inception (e.g., see summaries in Ellingson et al. 2016, Michalsky and Long 2016, Mlawer and Turner 2016, Stokes and Schwartz 1994). In its efforts to improve the representation of cloud and aerosol radiative effects in global climate models, ARM has fueled advances in radiometer and spectrometer measurement techniques and accuracies (e.g., Michalsky et al. 2002, 2003, 2005, 2006, Marty et al. 2003), retrieval development (e.g., Alexandrov et al. 2008, Chiu et al. 2012, Kassianov et al. 2007, Long et al. 2006, Lubin and Vogelmann, 2011, Michalsky and Long 2016, Shupe et al. 2016, Turner et al. 2007), and radiative transfer (Mlawer and Turner 2016, Turner et al. 2004). Notable successes have been achieved by ARM in spectral longwave (LW) measurements and radiative transfer modeling, developing the first field-based quantification of radiative forcing from rising atmospheric concentrations of carbon dioxide and methane (Feldman et al. 2015, 2018) and improving the accuracy of broadband surface measurements (e.g., Mlawer and Turner 2016, Marty et al. 2003). Shortwave hyperspectral measurements were not as critical to early ARM accomplishments in clear-sky radiation due to fewer problems in line-by-line radiative transfer in that spectral region than in the LW. The nearly exclusive focus on the LW was also enabled by technical advances in calibration in the LW that have yet to be achieved in the SW (Mlawer and Turner 2016). However, several recent developments in SW spectral measurement and retrieval technology, along with more ambitious science goals espoused by ARM, including strengthening links to earth system models (ESMs), make this an ideal time to revisit the scientific priorities behind SW spectral measurements at the ARM facility.

ARM's decadal vision (DOE 2014) has helped to clarify ARM's priorities in developing new techniques, including high-resolution modeling and distributed measurement networks, to gain further insight into subgrid-scale cloud, aerosol, and land surface processes driving the climate. These shifts in strategy demand new measurement techniques focused on the prioritized processes. At the same time, developments in SW spectral measurement technologies have the potential to impact atmospheric science in new ways. These developments include approaches that use ratios and the shape of hyperspectral measurements that partially remove dependencies on the absolute accuracy of calibration (Sections 3-4). Other new efforts include the work to add a 1.6-micron channel to ARM's filter-based measurements that represent the longest and most continuous records of SW spectral measurements at multiple sites and campaigns across ARM (Section 2), and new commercially available shortwave spectrometers that may complement ARM's paradigm and existing instrumentation (Section 5).

This report describes the results of a review meeting on shortwave spectral measurements in ARM in February 2019. The purpose of the review was to evaluate the high-impact scientific priorities from SW spectral measurements and make recommendations to ARM on a strategy for needed instruments, retrieval data products, and the data quality or measurement accuracy required to meet those scientific challenges. The meeting gathered experts from within and external to the ARM and Atmospheric System Research (ASR) communities to evaluate current scientific problems and retrievals using measurements as well as the current state of ARM measurements. The group identified two major areas where SW spectral measurements could lead to new observational constraints on priority research themes: 1) new retrievals of atmospheric constituents to address microphysical processes, and 2) understanding radiative effects in complex and heterogeneous environments. While examples were given of research in these areas by the group members, participants recognized that the potential for these measurements was much wider than the scientific expertise within the group. However, what this group did provide that is of value to the wider scientific community is an initial assessment of the potential and the limitations of SW spectral retrieval techniques and instruments in cloud, aerosol, land, and radiative observations. This information is compiled in this report and will be used to help spark the conversation about priorities and scientific needs within the broader ASR and scientific community.

2.0 Current Inventory of ARM SW Spectral Radiometry and Retrievals

The workshop included an overview of filter-based and hyperspectral SW radiance and irradiance measurements made by the ARM facility and some of the strengths and weaknesses of these measurement techniques. Appendix 1 includes a comprehensive list of SW spectral measurements that have been made by ARM over the years and that were discussed at the February meeting.

In addition to the summary of instrumentation and measurements available, several current and upcoming upgrades to the ARM instrumentation were discussed including: 1) exchanging the MFRSR broadband silicon channel for a 1625-nm filter to better constrain surface albedo, aerosol microphysical and optical properties, and cloud droplet effective radius; 2) replacing MFRSR heater boards to improve noise; 3) addition of a lunar mode for the Cimel sun photometer to add aerosol optical depth (AOD) retrievals in darkness, particularly at high-latitude sites over the polar winter; 4) new techniques to calibrate the shortwave array spectroradiometer–hemispheric (SASHE) and the shortwave array spectroradiometer–zenith (SASZE) using a combination of lamp and Langley calibrations and comparison to other instruments.

Additionally, several current projects were described that have added better data quality screening leading to higher confidence in the measurement data. Fast Fourier Transform tests have been added to the Data Quality Office screening of MFRSR data to better identify shading issues, one of the primary data quality concerns for MFRSR retrievals (Alexandrov et al. 2007). Comparisons between AOD retrievals, radiance, and irradiance measurements from multiple instruments at a site are also being used to identify periods of known good data quality, or good data epochs that will provide easily accessible, sound data sets for intensive research.

Recommendations: *The upgrades to the filter-based instruments and data quality screening to identify good data epochs were both viewed highly by workshop participants as high-priority next steps to hand higher-quality data to users that will be useful for needed retrievals as described in Section 3.*

3.0 Potential Scientific Impact of SW Spectral Measurements

We began the meeting with presentations from participants on how they were currently using SW spectral measurements in their research to frame the discussion based on scientific needs and priorities. The description of current studies and the potential of SW spectral measurements focused on two key scientific areas relevant to ARM and ASR's missions: 1) microphysical retrievals for process studies, and 2) radiative processes and distributed measurements. These are described in Sections 3.1 and 3.2.

While the group recognized that its role was not to make decisions about the highest-priority scientific questions for the programs, we wanted to provide information to help the larger community better understand the potential of SW spectral measurements for constraining process studies. More specifically, the group felt that the greatest need to make these measurements more scientifically impactful rests in expanding available parameters and improving data product accuracy through investments in retrieval development.

3.1 Microphysical Retrievals for Process Studies

A key topic of discussion at the workshop focused on the strides being made in cloud, radiative, and aerosol-cloud interaction process studies using the capabilities of SW spectral measurements to provide retrievals of cloud microphysical and radiative properties (e.g., optical depth, effective radius, drop number concentration, liquid water path, thermodynamic phase). Studies that were discussed included:

- High-latitude cloud-albedo interactions such as the influence of cloud effects during the West Antarctic Ice Sheet melt episode measured during the ARM West Antarctic Radiation Experiment (AWARE; Wilson et al. 2018)
- Constraining parameterizations of autoconversion and accretion rates in warm rain formation, critical for reducing uncertainty in aerosol-cloud interactions and thus climate change prediction (ongoing work extended from Fielding et al. 2015)
- Measuring the contribution of aerosol layers above cloud-to-cloud radiative effects (LeBlanc et al. 2019)
- Disentangle aerosol and cloud radiative effects for aerosol-immersed broken cloud fields from spectral irradiance measurements below clouds (Schmidt et al. 2009)
- Quantitative measures of the radiative forcing of aerosol-cloud interactions (Painemal et al. 2017, McComiskey and Feingold 2008, 2012, McComiskey et al. 2009)
- Ground-based SW spectral measurements that are uniquely able to provide observations of the clear-to-cloudy transition zone and the aerosol-cloud interactions in that zone, and are being used to identify when homogeneous and heterogeneous mixing processes are at work in cloud edges (e.g., Yang et al. 2016, Chiu et al. 2009, Yang et al. 2019)
- The need for better constraints on the SW water vapor continuum where there is disagreement in laboratory studies. Also, better measurements of gaseous absorption in the near infrared (NIR) for CO_2 and CH_4 as these radiative effects were not included in Coupled Model Intercomparison Project 5th phase (CMIP5) radiative transfer parameterizations.

3.1.1 Cloud Retrievals

While SW spectral radiation measurements played a key role in each of the above applications, all were done using retrievals implemented by the principal investigator (PI) and not from a standard ARM product. ***There was a general consensus in the group that the largest roadblock to the use of SW spectral measurements for cloud microphysical process studies was the need for more retrieval development.*** If optical depth, effective radius, cloud phase, and other cloud microphysical property retrievals were more readily available, then we anticipate they would be used by a greater number of researchers who do not have the time or expertise to implement those retrievals themselves.

Currently, the only operational cloud optical depth products run by ARM are the MFRSR Cloud Optical Depth product and the broadband optical depth retrieval included in the Radiative Flux Analysis product. These products are used by the community, but are limited to overcast, liquid, single-layer clouds over surfaces with a low albedo, so they do not apply to many of the cloud types and processes being actively studied by the ARM user community. A step in the right direction is the Cimel-based 3-wavelength optical depth and effective radius (Chiu et al. 2012) retrieval product currently being implemented by the mentor group at Brookhaven National Laboratory, as the zenith radiance allows cloud retrievals that match the field of view of active instruments in broken clouds. However, the low temporal frequency of Cimel cloud measurements, limited wavelengths of the Cimel, and potential errors from 3D effects (Masuda et al. 2019) still have limitations and do not capture the full potential for cloud retrievals.

Two important areas of needed growth in cloud retrievals from ARM SW spectral measurements are implementation of retrieval methods that can operate under a broader range of conditions, and a need to better understand the uncertainty of differing retrieval methods.

The workshop discussed a number of cloud retrieval methodologies that can operate under a broader range of conditions. A complete list of potential cloud retrievals in the literature is given in Appendix 2.

Retrievals based on hyperspectral measurements have several advantages over filter-based retrievals. One of the advantages of using hyperspectral measurements is that methodologies can be used that are based on the shape of the spectra rather than depending on the absolute accuracy of calibration. Some of the methods discussed include optical depth and effective radius retrievals based on the slope of the spectra in the near IR (McBride et al. 2011, 2012, Wilson et al. 2018), optical depth using the shape of the oxygen-A band to distinguish between optically thin and thick cloud transmissions (Niple et al. 2016), optical depth and effective radius retrievals in the transition zone between clear and cloudy zones using the spectral invariance of the slope of the visible band and the intercept of the near-infrared band (Marshak et al. 2009, Yang et al. 2016), and a retrieval of phase, and optical depth and effective radius of liquid and ice clouds over surfaces of any albedo, using 15 parameters that describe the shape of the SW spectra (LeBlanc et al. 2015).

Additionally, hyperspectral retrievals have been developed that allow for more flexibility in retrieval conditions. Some of these methodologies allow for retrievals in high latitudes with ice-and-snow-covered ground (e.g., Wilson et al. 2018, LeBlanc et al. 2015), of clouds over ocean (e.g., McBride et al. 2012, Brückner et al. 2014), and in complex cloud and aerosol mixtures (Marshak et al. 2009, Yang et al. 2016, Schmidt et al. 2009). All above-mentioned retrievals are based on zenith radiance measurements and are available in broken cloud conditions (though the uncertainties in these conditions are still not well quantified), and some can operate under conditions of either ice or liquid clouds (Niple et al. 2016, LeBlanc et al. 2015).

Ground-based sampling of cloud properties using solar-transmitted light has some distinct advantages, while still facing challenges. Measuring radiant energy transmitted through clouds can enable studies in cloud processes at a high time interval, focusing on locations seldom measured or hard to retrieve from space-based observations, focusing on a different cloud-sampling volume, and more directly relating to surface-based energy budgets. Sampling the radiant energy from below clouds has the potential to alleviate issues with remote sensing with a direct view of the cloud's underside and has a direct link to the changes of surface energy budget. By using cloud-transmitted light rather than reflected light, the sampled photons have travelled through the cloud vertical column, resulting in an effective sampling volume evenly spread throughout the cloud, unlike reflected light, which is more dependent on the top few optical depths of cloud (Platnick 2000, LeBlanc et al. 2015). The mapping from hyperspectral measurements to cloud properties requires a retrieval algorithm. Applying typical reflectance-based cloud property retrievals (Nakajima and King 1990) to transmittance measurements leads to non-unique solutions, where two radiances are linked to the same cloud properties. Hyperspectral observations have been used to solve this ambiguity in various ways including spectral slopes (LeBlanc et al. 2015, Kikuchi et al. 2006), and the width of the oxygen-A band (Niple et al. 2016), though investigating the best methods in inhomogeneous cloud conditions requires additional research due to spectral perturbations (Song et al. 2016) that can corrupt their information content and render traditional retrieval inaccurate. Using 3D spectral signatures (see Section 3.2) and spatial context from additional measurements (Masuda et al. 2019) to improve retrievals under inhomogeneous conditions is an emerging research direction, which the ARM facility could tap into.

In addition to retrieval methods that can operate in new conditions beyond the limited cloud retrievals available in official ARM products, the group discussed the importance of understanding the accuracy and uncertainty of new retrieval methods. For example, Christine Chiu discussed that in order to use SW spectral measurements as a constraint with active sensors in multi-instrument retrievals of drizzling clouds, absolute zenith radiances needed to be accurate to within 5%. Some of the new methodologies using the shape of SW spectra in hyperspectral measurements have not yet been tested in multi-instrument retrievals with active sensors, though comparisons between retrievals using the LeBlanc et al. (2015) methodology showed 2.5 times less uncertainty in effective radius retrievals than a two-wavelength method (Kikuchi et al. 2006) in case studies. Quantifying uncertainty in cloud microphysical retrievals can be very challenging as it is difficult to find a ground-truth data set by which to define the uncertainty.

Nevertheless, several paths forward for improved understanding of retrieval uncertainty were identified by the group. First, it was proposed to develop a structure for understanding the closure or consistency between the set of microphysical properties retrieved from SW spectral radiation measurements and those from other independent instrumentation such as microwave radiometer liquid water path retrievals. This was also deemed to be extremely valuable for operational understanding of uncertainties that incorporate field measurement challenges in instrument operation as well as retrieval applicability. Second, better statistical analyses of the information content within the retrievals, such as the LeBlanc et al. (2015) parameters, was recommended as a necessary step for developing an operational retrieval that could help distinguish between retrieval ambiguities and the sensitivity to instrument errors. Finally, it was identified as a high priority to determine data epochs of good-quality hyperspectral and filter-based measurements that could be used to test and compare new retrieval methodologies. Many promising current retrieval methodologies have only been applied to case studies, where a scientist is closely looking at the data. Before these could become operational retrievals, they would need to be tested on longer periods of data.

Recommendations: *The biggest need to make SW spectral cloud retrievals accessible to the broader community for process-based studies is to support retrieval development activities from SW spectral measurements. The ultimate goal should be a high-temporal-resolution, zenith-radiance-based, cloud retrieval capable of retrieving cloud optical depth and effective radius in broken-cloud conditions for liquid and ice clouds, with any surface type. Initial steps to support this retrieval development were* *recommended to include: providing good data epochs of spectral measurements to give the community a testbed for retrieval development, uncertainty analysis, and process studies; supporting retrieval intercomparisons of new methodologies and their closure with independent measurements (e.g., microwave radiometer liquid water path); and statistically robust assessments of information content in new retrieval methodologies.*

3.1.2 Aerosol Retrievals

The Earth's radiation budget changes due to variability in aerosol loading and properties on regional and global scales are commonly quantified by direct aerosol radiative forcing (DARF). Both the magnitude and sign of DARF depend on AOD, single-scattering albedo (SSA), and asymmetry parameter (ASY) (e.g., McComiskey et al. 2008, Sherman and McComiskey 2018), which define the columnar abundance of the atmospheric aerosol and its absorbing and scattering properties, as well as on the spectral surface albedo and solar geometry. However, information on these aerosol properties is largely confined to near-surface measurements (e.g., Andrews et al. 2019). Moreover, these measurements typically represent a quite narrow spectral range (0.45-0.7 μm), while a much wider spectral coverage is required for accurate radiative transfer (RT) calculations of DARF. In addition, an extrapolation of the aerosol properties obtained from measurements with narrow spectral width to unspecified wavelengths may result in substantial differences between calculated and measured surface irradiances (Michalsky et al. 2006). Ground-based radiometers are particularly suited to retrieve aerosol properties because of their potential for wide spectral coverage.

Discussion of aerosol retrievals at the meeting focused in particular on the potential of the new MFRSR 1.6-micron channel, multi-instrument retrievals of aerosol properties, and the utility of spectral measurements in the ultraviolet range for better constraining aerosol absorption properties as discussed further in Section 3.2.

The expected new 1.6-μm MFRSR channel would create a unique opportunity to improve the MFRSR retrievals of supermicron particles, and thus to improve characterization of the AOD changes across a wide spectral range. The wide range of AOD retrievals are desired for reliable estimation of aerosol particle size distributions, which impact human health, the environment, and the climate (e.g., Hand et al. 2017). Further, a better estimate of the size distribution will yield smaller uncertainties in retrievals of aerosol optical properties. Particle size distributions commonly have fine and coarse modes with submicron and supermicron particles, respectively. These two modes define how the AOD changes with wavelength for a given complex refractive index (e.g., Schuster et al. 2006). The AODs measured in near-infrared spectral channels (wavelengths above 1 μm) are sensitive to the coarse mode (e.g., Sayer et al. 2012; Figure 1). In turn, such AOD characterization is needed for improved retrievals of the SSA and ASY and anticipated retrievals of greenhouse gases from complementary hyperspectral measurements (e.g., Segal-Rosenheimer 2014). We recommend that the MFRSR AOD and aerosol-intensive property retrievals be updated to take advantage of this new spectral information using look-up tables for the 1.6-um channel.

Multi-instrument retrievals of aerosol properties have the potential to better constrain aerosol optical and microphysical properties. Constraining lidar profiles of aerosols with column-integrated retrievals from passive SW spectral measurements has been identified as an important strategy in accurate retrievals of aerosol profiles (Tesche et al. 2008, 2019). Column-integrated retrievals of SSA and ASY themselves can benefit from sensor synergy between two commonly deployed filter radiometers, the Cimel sunphotometer and MFRSR (Dubovik and King 2000, Kassianov et al. 2007). Both instruments use total, direct, and diffuse components of the radiation to derive aerosol properties but their different measurement approaches − sun-tracking and almucanter scans versus subtraction of total and diffuse components to produce the direct-beam component − yield relatively higher sensitivities to these aerosol properties in high (Cimel) versus low (MFRSR) aerosol loading conditions. A combined aerosol optical properties data product would provide a more consistent and accurate set of retrievals across a range of conditions.

Another example of a multi-instrument method that could improve current aerosol retrievals is integrating total sky imager (TSI) images to improve identification of cloud-free conditions. The existing CSPHOT-based (Dubovik et al. 2000) and MFRSR-based (Kassianov et al. 2007) retrievals of SSA and ASY require “cloud-free” conditions, and different criteria are used for their identification. For the CSPHOT-based retrievals, such identification is based on the sky brightness uniformity and includes this criterion: 20% agreement for sky radiance symmetry check for all angles except 180° azimuth (Holben et al. 2006). For the MFRSR-based retrievals, such identification is based on “hemispherically clear-sky” periods but with reduced sensitivity to clouds close to the horizon. These periods could also be identified using broadband solar measurements (Long and Ackerman 2000) and/or TSI images (Long et al. 2001). However, the required “hemispherically clear-sky” periods substantially reduce the amount of time when the MFRSR-based retrieval can be applied. Likely, it can be performed with some clouds in the sky as long as those clouds have only a small contribution to the diffuse irradiances measured at the surface. It can be expected that low clouds located near the horizon will contribute slightly to these irradiances and fractional sky covers (FSCs) provided operationally from TSI images with 100- and 160-deg fields of view (FOVs) will identify these cases. However, even under “cloud-free” conditions, it is important for aerosol loading to be spatially uniform. The CSPHOT-based information on the sky brightness uniformity can be used to assess the spatial homogeneity of aerosol.

Recommendations:

- *Update AOD and aerosol-intensive property retrievals for a wider spectral range using the new 1.6-um MFRSR band.*
- *Develop a combined data product for aerosol optical properties − AOD, SSA, and ASY − from passive filter radiometers (Cimel and MFRSR).*
- *Strengthen retrievals of vertical profiles of aerosol optical properties using the synergy between active and passive remote sensors.*
- *Provide an improved “cloud-free and spatially homogeneous sky” identification required for the MFRSR-based retrieval of the aerosol SSA and ASY by combining measurements of the sky brightness and broadband surface irradiance with the 100- and 160-deg FOVs FSCs obtained from TSI images.*

3.1.3 Radiative Parameter Retrievals

Discussions on retrievals of radiative parameters from existing spectral measurements revolved around two topical areas where SW spectral measurements (particularly from MFRSRs) could provide needed information: surface albedo and photosynthetically active radiation (PAR). Surface albedo measurements were discussed in the context of needs for the land-atmosphere interactions community to better define surface types and associated fluxes, and a measurement of PAR would help engage the ecological community, particularly in the Azores around ARM's Eastern North Atlantic (ENA) atmospheric observatory.

Surface albedo modulates the surface energy budget and is used as an input to aerosol and cloud retrievals. Albedo was shown to be a relevant source of uncertainty in model temperature biases over the Southern Great Plains (SGP) site in the Clouds Above the United States and Errors at the Surface (CAUSES) campaign (Zhang et al. 2018), albedo heterogeneity of the land surface is an important piece of land-atmosphere studies, and albedo can help determine the causes and improve simulations of snow melt. The current spectral albedo product effectively interpolates multifilter radiometer (MFR) data at the SGP and North Slope of Alaska (NSA) sites (McFarlane et al. 2011, https://arm.gov/capabilities/vaps/surfspecalb) to provide a full spectral albedo useful for radiative studies and aerosol-intensive property retrievals. There is significant uncertainty in the albedo in the near IR due to few measurement constraints in that region. With the new 1625-nm MFR channel currently being installed, and the potential of calculating albedo using new upward-facing-only measurements (Kassianov et al. 2014, 2017) including the SASHE, a greater constraint on the near IR can be applied with further retrieval development.

One area of particular interest discussed at the meeting was the albedo of snow and the feedbacks between clouds and snow/ice melt. Dan Lubin described the success of using SW spectral measurements to understand cloud properties and their relationship to ice melt during AWARE. The potential of long-term albedo measurements at NSA sites would enable studies of the temporally varying contribution of snow-grain size and impurities to surface albedo and their relationship to seasonal melt. The albedo of frozen surfaces varies strongly in the spectral dimension: over visible wavelengths, it can be highly reflective and differ from a perfect reflector by only a few percent with fresh snow, while over near-infrared wavelengths, its reflectivity around 1500 and 2000 nm can approach that of a perfect absorber. This albedo also varies strongly with snow-grain size (Wiscombe and Warren 1980), shape (Dang et al. 2016), and the presence of impurities (Warren and Wiscombe 1980). Significant work has been undertaken to model the role of impurities in impacting frozen -surface albedo (e.g., Flanner et al. 2005, Skiles et al. 2018), since it has a significant impact on climate model performance and fidelity (e.g., He et al. 2017). Dang et al. (2016) highlighted the challenges of incorporating natural snow crystal shape for different snow age and meteorological conditions in climate models, but this information is attainable with ARM data. Retrievals of spectrally resolved surface albedo from the currently available retrieval product could be augmented to provide: 1) retrievals of snow-grain size based on a sphericity assumption; 2) comparisons of radiative transfer calculations and observations to assess whether the sphericity assumption is warranted; and 3) retrievals of effective snow impurity concentration. ARM observations could provide time-varying information of deposited aerosols, including their chemical, optical, morphological, and hygroscopic properties, and this information can determine the controls on the mixing state of snow and impurities. This is of particular interest during the melt season where it has been shown that snow-grain and impurities can interact in a highly nonlinear way to influence albedo (He et al. 2017, 2018).

PAR is the part of the solar spectrum that occurs non-linearly between 400 and 700 nm and is used by photosynthetic organisms in the process of photosynthesis. PAR is an important parameter for scientists studying problems associated with the life cycle of plants. At the University of the Azores, there is an emphasis on ecological applications including agricultural applications and marine biology. Scientists there have expressed a specific interest in measurements of PAR at ARM's ENA site on Graciosa Island.

More generally, providing measurements of PAR, in combination with other meteorological measurements provided at all ARM sites, would significantly increase the value of these sites to scientists in ecological or agricultural sciences. Currently, the SGP is the only ARM observatory with a direct measurement of PAR; however, PAR can be estimated through a linear combination of MFRSR channels in the PAR range. This is done by 1) using calibrated irradiances from several MFRSR bands (415, 500, 615, 673 nm) within the PAR spectral range combined linearly to estimate PAR; 2) generating coefficients for each channel using collocated vis-MFRSR observations against spectral solar irradiance measurements preferably from a National Institute of Standards and Technology (NIST)-traceable spectroradiometer weighted with the PAR action spectrum, (400-700 nm) or as a check using a calibrated PAR sensor (e.g., Trisolino et al. 2016, 2017). The World Meteorological Organization (WMO) Baseline Surface Radiation Network (BSRN) spectral committee is currently discussing a PAR intercomparison campaign with a field component comparing at least three radiometers per manufacturer to a well-calibrated traceable spectroradiometer, and a laboratory component characterizing the spectral and cosine response of the different instruments per type, e.g., broadband and filter radiometers. Participating in this campaign would help ensure the accuracy of PAR measurements.

Recommendations: *Incorporate the 1.6-micron MFRSR channel into the ARM albedo product to better constrain the impact of land surface type on the full spectral albedo product including snow and ice at NSA for studies of snowmelt conditions. In addition, assessing the spatial heterogeneity of albedo at ARM sites was discussed as an important step for model evaluation and satellite validation.*

A PAR product can be developed from MFRSR measurements in comparison to a PAR sensor. This can be used to retrieve PAR at ENA and possibly other sites to broaden the utility of ARM measurements. In order to ensure the accuracy of the method, the group recommended participation in the PAR intercomparison being planned by the spectral committee of the WMO BSRN.

3.2 Radiation Budget Studies and Distributed Measurements

While broadband radiation measurements are commonly used to track changes in the Earth's surface radiation budget, spectral measurements enhance understanding of these changes and the processes by revealing the physical mechanisms responsible. In addition to the work described above designed to advance retrievals of cloud and aerosol microphysical and radiative properties for process studies, there is potential for the same SW spectral radiation measurements to be tapped directly for radiation budget studies.

Closing the radiation budget, globally or even at the regional scale, has remained a challenge through time, which speaks to inaccuracies in our ability to retrieve and represent atmospheric components like aerosols, clouds, and surface albedo in complex environments. These inaccuracies can then feedback into our ability to distribute radiation correctly and accurately represent dynamics. Hyperspectral measurements have potential to shed new light on separation of radiative effects in complex environments through closure studies, retrievals of aerosol radiative effects in complex environments, and a better constraint on 3D radiative effects. Mismatches in surface fluxes derived from top of atmosphere with measured surface fluxes likely result from the effects of horizontal photon transport and our lack of ability in the past to implement 3D radiative transfer as well as an inability to separate aerosol, surface albedo, and cloud radiative effects.

This problem may benefit from the development and application of 3D radiative transfer. It has also been demonstrated that detailed cloud macro- and microphysical properties retrieved from radiance and irradiance measurements can close the radiation budget better than direct observations of the radiation budget components, so these different application classes – cloud and aerosol property retrievals and radiation budget studies – are intimately related.

Areas of research relevant to radiation budget studies that were discussed are:

- Radiative effects in complex aerosol-cloud-surface fields
- Clear-to-cloud continuum
- Modeling of radiation budget
- Distributed measurements for characterizing spatial heterogeneity.

Spectral radiometry provides the ability to determine the radiative forcing contributions of atmospheric constituents – aerosol versus cloud versus gases. This is particularly important in complex aerosol-cloud-surface fields where a multiple-scattering environment can complicate attribution to any one process. For example, broken cloud fields in a high-aerosol environment or over a heterogeneous surface can result in complex scattering and absorption processes that are exceedingly difficult to disentangle using simple observations and models. High-resolution spectral irradiance coupled with 3D radiative transfer has been shown to provide detailed and accurate information regarding the contribution of aerosol and cloud scattering and absorption in such an environment (e.g., Schmidt et al. 2009). Similar results can be achieved without hyperspectral data and using filter-based methods (e.g., MFRSR) that ARM currently operates if the signatures of interest from aerosol and cloud are already known. However, hyperspectral measurements provide the advantage of visualizing slopes or the wavelength dependence of irradiance in each particular environmental situation that can be exploited to characterize the environment. This is most successful when used in conjunction with 3D radiative transfer to substantiate the controls on the observed irradiance patterns. Current filter-based instrumentation is designed well to identify aerosol properties, but a large gap between 1.0 and 1.6 um results in missing information for clouds and gases. Furthermore, if aerosol brown carbon is of interest, targeting wavelengths in the ultraviolet portion of the spectrum, not currently covered routinely by ARM radiometers, would be important. It was recommended that the high-quality data epochs discussed above be used to test the capabilities of existing spectral measurements from the Layered Atlantic Smoke Interactions with Clouds (LASIC)/Observations of Aerosols above Clouds and their Interactions (ORACLES) campaigns to explore potential in high-aerosol loading where surface properties are relatively homogeneous and well characterized.

The clear-to-cloud continuum is a critical space for improving radiation budget estimates and aerosol-cloud processes. This region encompasses a large proportion of atmospheric conditions but is often excluded from analysis due to its ambiguity and complexity. As the cloud edge is approached, increased humidification leads to increased light scattering and radiative effects near cloud edge behave as a continuum from the clear-to-cloud state. However, the specific radiative effects depend on cloud processes (e.g., homogeneous versus inhomogeneous mixing, Chiu et al. 2009, Yang et al. 2019) that control both aerosol and cloud microphysical properties. For radiation budget estimates typically made from space-based sensors (e.g., Kato et al. 2013) but more recently enhanced using ground-based measurements (Wild et al. 2013), the omission of the transition zone through masking to create cloud and aerosol products yields biases in the estimates. About 20% of all Moderate Resolution Imaging

Spectroradiometer (MODIS) pixels are too cloudy to be retrieved by the aerosol algorithm and not cloudy enough to be retrieved by the cloud algorithm: thus, they are unaccounted for in global estimates of clear-sky and cloudy-sky radiative effects. Observations within this region can be used to further aerosol-cloud interaction process understanding and inform radiation budget studies from both ground and space, reducing the associated uncertainties. Several measurement options that draw on instrumentation currently deployed by ARM were discussed to better characterize the transition zone. These include, but are not limited to, high-temporal-and-spectral-resolution measurements at the cloud edge, the use of the normal incidence multifilter radiometer (NIMFR) with a narrow field of view oriented to capture scattering angles that inform transition zone properties, and statistical analyses using sky imaging and filter-based measurements (Calbo et al. 2017).

It has been noted that the radiation budget can be closed more accurately using retrieved cloud properties and models to simulate radiation rather than observations of radiative fluxes at the surface and top of atmosphere. However, Jake Gristey showed in recent large-eddy simulations (LES) over the SGP in shallow broken cloud conditions that a domain-averaged calculated broadband irradiance compared to observations at a point showed poor closure. However, using on the order of 10-point observations distributed over the domain (from extended facilities), the comparisons improved markedly. This goodness of closure will depend on cloud field morphology. These results point to the criticality of spatially distributed measurements for evaluating simulated radiative effects in process-scale models and the role that such distributed measurement networks might play in the success of efforts such as LASSO. While this demonstration was made using the available broadband measurements at extended facilities, distributed spectral irradiance would provide the ability to diagnose the drivers of spatial variability in irradiance, such as the aerosol, cloud, and surface effects as discussed above. While distributed measurements at SGP are possible through the existing extended facility infrastructure, new locations would require a plan for establishing a network. Considerations would include the domain size and density of measurements as well as the suite of measurements required at each site for addressing particular applications. The applicability of high-quality miniaturized instrumentation or simplified radiometers such as the sunshine pyranometer (SPN)/hyperspectral pyranometer (HPN) were discussed in this regard.

Recommendations: *Existing measurements have the potential to test new techniques in observing aerosol and cloud radiative effects in complex environments such as absorbing aerosol in broken cloud conditions, and the transition between clear and cloudy regions. To facilitate these studies, it was recommended that observational data from the LASIC campaign be included in the data epoch work.*

4.0 New Instruments and Approaches

We discussed some of the new hyperspectral commercial instruments on the market and under development. The growth in this industry warrants close attention by ARM, as new commercially available instrumentation might have the potential to meet ARM’s needs for spectral measurements in the near future. Steve Jones and Herman Scott from Aerodyne, Inc. presented information about the current version of the three-waveband spectrally agile technique (TWST), which uses hyperspectral zenith radiance measurements from a silicon channel spectroradiometer to retrieve cloud optical depth with high temporal resolution in most conditions (Niple et al. 2016). The TWST has already been fielded at several ARM campaigns including the Two-Column Aerosol Project (TCAP) and Biogenic Aerosols − Effects on Clouds and Climate (BAECC). One of the advantages of the TWST is that it also includes software with a new retrieval technique that uses the shape of the oxygen-A band to distinguish between optically thin and thick cloud transmittance. Aerodyne is currently working on adding an additional sensor on the near infrared to extend the capabilities of the TWST. These longer wavelengths will enhance the ability of the instrument to provide cloud microphysical properties including phase in a range of conditions.

While John Wood from Delta-T devices was not able to attend the meeting, Sebastian Schmidt has fielded a prototype of Delta-T's HPN1 hyperspectral irradiance measurements on aircraft campaigns and on the ground and found the performance to be equivalent to his laboratory's custom-built solar spectral flux radiometer (SSFR). This instrument uses similar shading technology to the broadband SPN1 that requires no moving parts and ARM has deployed on both ship and aircraft.

Dan Lubin purchased a spectrometer from StellarNet (https://www.stellarnet.us/spectrometers/) for less than $20,000 for his own research. The instrument setup he purchased can measure irradiance or zenith radiance and consists of a diffusing optical collector connected by a split fiber-optic cable to two separate spectrometers: one with a Si linear array detector for UV/visible light and another with an InGaAs linear array for near-infrared (NIR) light. Dan volunteered to report on the quality of the data in the future after he has taken measurements in the field.

These three examples are not meant to be exhaustive, but illustrate the maturation of hyperspectral technology in recent years that may allow ARM to shift towards more commercial instrumentation and even retrieval methodologies in the near future that will be more efficient in terms of calibration, deployment, and production of data as well as being more cost effective.

Recommendations: *Continue to follow the development of commercial instrumentation like the TWST and HPN1 and facilitate intercomparisons with current ARM instrumentation when these new instruments are ready. In the future, evaluate whether these new commercial instruments, particularly those which include retrieval algorithms, might be a good fit for ARM's spectral radiation needs.*

5.0 Summary of Meeting Outcomes and Recommendations

The clear message from the meeting was that SW spectral measurements have great potential to impact process-based studies in innovative ways through retrievals of cloud and aerosol microphysical and radiative properties, and to constrain surface and atmospheric properties needed for better radiative studies. **The group felt that the greatest need to make these measurements more scientifically impactful rests in expanding available parameters and improving data product accuracy through investments in retrieval development.**

We identified four main outcomes or sets of recommendations from the meeting:

1. *Increase communication of availability of ARM SW Spectral data with wider radiation, atmospheric science, and remote-sensing communities.* One of the productive aspects of the strategy review was engaging with leading spectral radiation scientists outside of the ARM/ASR community, which allowed the cross-fertilization of ideas and retrieval methods. The group plans to continue this momentum by publishing an article in *BAMS* on the ARM SW spectral measurements and how they might be used to increase engagement with a broader community.

2. *Provide SW spectral data epochs to facilitate easier retrieval development, intercomparisons, and process-based studies.* We identified several case studies of interest to those at the meeting to allow instrument mentors to prioritize examining the data quality of measurements. These are listed here in order of priority:
    - TCAP: This campaign includes the TWST instrument, upward- and downward-looking MFR(SR) with 1.6-um channels, Cimel, SASHE, and SASZE. The campaign was held in a complex coastal environment giving a variety of albedo, cloud, and aerosol conditions for studies of multiple processes of interest and a range of cloud retrieval testing.
    - ACE-ENA (Aerosol and Cloud Experiments in the Eastern North Atlantic): While there were fewer spectral measurements here, hyperspectral zenith measurements from the shortwave spectroradiometer (SWS) can be used to determine accuracy and utility of cloud retrievals in broken-cloud and multi-instrument retrievals. Specific questions of interest were drizzle formation and warm-cloud microphysics.
    - LASIC/ORACLES: This campaign would allow examination of the potential for retrievals and radiative calculations in complex aerosol and cloud environments.
    - SGP measurements were also discussed as of interest. SGP has multiple hyperspectral measurements (e.g., rotating shadowband spectroradiometer [RSS] and shortwave array spectroradiometer [SAS] simultaneous measurements), multiple MFRSRs, NIMFRs, Cimels, etc. The primary scientific motivation for this site is the work with shallow broken clouds (e.g., LASSO) and land-atmosphere interaction studies that would benefit from improved cloud and albedo retrievals.
    - The NSA Barrow site was discussed as advantageous for studies of ice melt and cloud properties. Cloud microphysical and optical retrievals were thought to be especially useful given the challenges of operating microwave radiometers in these conditions. This would yield independent measurements that could be used in concert with liquid water path measurements for quality control and retrieval evaluation. This site was also deemed a high priority for albedo retrieval development to study ice and snow melt.
3. *Supporting retrieval development was identified as a key recommendation of this strategy review.*
    - The highest need discussed was to develop better cloud retrievals. The ultimate goal should be a high-temporal-resolution, zenith-radiance-based cloud retrieval capable of retrieving cloud optical depth and effective radius in broken cloudy conditions for liquid and ice clouds, with any surface type. This should include work to evaluate the accuracy of the retrieval using retrieval intercomparisons, closure intercomparisons with other measurements, and statistical assessments of information content in SW spectral data. While many retrieval approaches exist in the literature (Appendix B), the group assessed that the current maturity of the algorithms was not such that clear choices should be operationalized into a value-added product (VAP), but that more development is needed to fine-tune the algorithms for automated retrievals.
    - One identified area of low-hanging fruit was to update MFRSR retrievals of albedo and aerosol properties to include information from the new MFRSR 1.6-um channel.
    - Several multi-instrument aerosol retrievals were discussed as areas that would help move the measurements forward. These were:

    - A combined data product for aerosol optical properties − AOD, SSA, and ASY − from passive filter radiometers (Cimel and MFRSR).
    - Strengthen retrievals of vertical profiles of aerosol optical properties using the synergy between active and passive remote sensors.
    - Provide an improved "cloud-free and spatially homogeneous sky" identification for the MFRSR-based retrieval of the aerosol SSA and ASY by combining measurements of the sky brightness and broadband surface irradiance with the 100- and 160-deg FOVs FSCs obtained from TSI images.
  - Retrievals of PAR were discussed as they had been requested by partners at the ENA site. A good path forward to address this request would be to implement an MFRSR-based retrieval and evaluate its accuracy with the proposed BSRN PAR measurement intercomparison.

4. *New commercially produced hyperspectral instrumentation is in development and could provide a good path forward for future ARM measurement needs.* The group recommended that scientific priorities for retrievals should set the agenda for what instrumentation is of most value to ARM. To facilitate that discussion, Appendix B was created to provide information on what cloud retrievals already exist in the literature and what measurements they rely on for cloud retrievals. When scientific priorities are more clearly determined, it will be easier to evaluate new instrumentation on the market through intercomparisons with existing ARM instrumentation.

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Appendix A

Table of ARM SW Spectral Measurements

Table listing filter-based and hyperspectral measurements fielded by the ARM facility in at least one site or field campaign over the years. “Date routine” column refers to the date when it was first made routine at SGP if that was its first site. Measurement column uses abbreviations: irrad=hemispheric irradiance; dirh=direct horizontal irradiance; difh=diffuse horizontal irradiance; toth=total hemispheric downwelling irradiance; dirn=direct normal irradiance; rad=narrow field of view radiance. “Ch or spec” column gives the number of discrete channels when a filter-based measurement is described or the number of individual spectrometers for hyperspectral measurements. “WL” column lists the wavelengths measured for filter-based measurements or the wavelength ranges for hyperspectral measurements in nm. The final column describes orientations, scanning strategies, field of view, or information about where the instruments were deployed for guest instruments.

Table 1. ARM SW spectral measurements.

Instrument	Date routine	Measurement	Ch or spec	WL (nm)	Comment, modes:
MFR 10m	1994-03	irrad	7	415, 500, 615, 673,870,940,Si	upwelling hemisp, 10-m tower
MFR 25m	1994-03	irrad	7	415, 500, 615, 673,870,940,Si	upwelling hemisp, 25-m tower
MFRSR	1997-01	dirh, difh, toth	7	415, 500, 615, 673,870,940,Si	shadowband direct horizontal, diffuse hemisp, total hemisp
CIMEL	1998-03	dirn, rad	7	340, 380, 440, 500, 675, 870, 1020, (1640)	sun-tracking, sky-scanning, cloud-zenith, 1640 nm after 2007-03
NIMFR	1997-08	dirn	7	415, 500, 615, 673,870,940,Si	direct normal
NFOV	2000-03	rad	1	870	1.2 deg zenith
NFOV2	2004-09	rad	2	673, 870	1.2 deg zenith, moved to AMF1 after 2006-11

Instrument	Date routine	Measurement	Ch or spec	WL (nm)	Comment, modes:
RSS105	2003-05 - 2007-12	dirh, difh,toth	1	Si (360-1070)	
RSS	2009-08 - 2014-03	dirh, difh,toth	1	Si (360-1070)	Refurbished in 2009
SWS	2006-05	rad	2	Si (350-1000), InGaAs (970-2200)	1.4 deg zenith, moved to ENA in 2016-04
SASHe	2011-03	dirh, difh,toth	2	Si (350-1000), InGaAs (970-1700)	
SASZe	2011-03	rad	2	Si (350-1000), InGaAs (970-1700)	1 deg zenith
TWST	Guest inst.	rad	1	Si (350-1000)	Aerodyne, Scott, AMF1 TCAP 2013/5-6, AMF1 BAECC 2014/7-8
ASD	Guest inst.	toth (flux)	2	Si (350-1000), InGaAs (970-2200)	Lubin, NSA 2008/4-5 (ISDAC), NSA 2009/4-10, AWARE

Appendix B

Table of Cloud Retrieval Methods from SW Spectral Measurements

The following table contains a list of cloud retrievals from SW spectral measurements found in the literature that are potentially applicable to transmittance measurements such as those from ARM ground-based measurements. While likely not exhaustive, it gives a relatively robust picture of what cloud retrievals are possible from the measurements as evidenced by peer-reviewed literature. The physical retrieved quantities in column 2 describe whether optical depth (tau), effective radius (ref), liquid water path (lwp), cloud hydrometeor phase (phase), cloud fraction, or cloud albedo are retrieved by the method. The "Focus" and "Where/Notes" columns describe the conditions for which the retrievals were developed or other notes on the methodology. The following two columns indicate whether the retrievals are valid for zenith radiance (e.g., applicable to Cimel, SWS, SASZE) or irradiance (e.g., MFRSR, RSS, SASHE) measurements, where g/d refers to irradiance measurements that include both Global and Diffuse components. The "Hyperspectral" column indicates when hyperspectral measurements were used with an 'x' and multi-spectral or filter-based measurements with 'm/s'. In the final column, 'Surface-based' refers to whether the retrievals were developed using surface-based measurements, where a/c refers to the use of aircraft measurements.

Table 2. Cloud retrieval methods from SW spectral measurements.

Papers/name	Result/Physical quantities	Focus	Where/Notes	Zenith radiance	Zenith irradiance	Hyper-spectral	Surface-based
McBride et al., 2011, 2012	tau, ref, lwp (liq)	liquid cloud retrieval	ship, dark surfaces	x	x	x	x
LeBlanc et al., 2015	tau, ref, phase, (liq+ice)	liquid/ice cloud retrieval	ground site, various surfaces	x		x	x
Coddington et al., 2013	tau, ref	sensitivity to surface albedo	Vegetated and bare soils, ocean, snow, and SGP	x		x	x
Chiu et al., 2006, 2009, 2010	tau	cloud	vegetated surfaces	x		m/s	x
Wilson et al., 2018	tau, ref	cloud ice	Antarctic, snow/ice	x		x	x

Papers/name	Result/Physical quantities	Focus	Where/Notes	Zenith radiance	Zenith irradiance	Hyper-spectral	Surface -based
Niple et al., 2016	tau	cloud retrieval	TCAP, using oxygen-a band	x		x	x
Marshak et al., 2004	tau	cloud	over vegetated surfaces	x		m/s	x
Min and Harrison, 1996, 1999	tau, lwp	Cloud and photon path length	SGP		x	m/s	x
Min et al., 2008	cloud fraction	Scattered clouds	SGP		g/d	m/s	x
Min and Duan, 2004	lwp, ref	thin clouds	forward scattered lobe, multiple shadow-band measurements		g/d	m/s	x
Min et al., 2004	tau	thin clouds	theory		g/d	m/s	x
Kikuchi et al., 2006	tau, ref (liq)	liquid clouds, in absence of drizzle	Using water absorption bands		x	m/s	x
Daniel, 2002, et al., 2003, 2006	tau, ref, plwp, phase	water absorption features	DOAS, using path-integrated instead of vertical liquid water path Lab + ground + ac	x		x	x + a/c
Schofield et al., 2007	plwp, ref	comparison to microwave	DOAS + MWR + zen r, Barrow, Alaska	x		x	x
Harrison and Michalsky, 1994, Min and Harrison, 1996	lwp	Warm clouds	ARM SGP	x		m/s	x
Rawlins and Foot, 1990	tau, ref	stratocumulus	Transmittance ref has high uncertainty		x	m/s	x
Liu et al., 2011	cloud albedo and radiative forcing	Warm clouds (single- and multi-layered)	SGP		x		x

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