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ARM Aerosol Measurement Science Group 2024 Strategic Planning Workshop Report

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ARM

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Executive Summary

This report summarizes the results of the 2024 Strategic Planning Workshop conducted by the Aerosol Measurement Science Group (AMSG) for the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) User Facility. The objective of this workshop was to provide ARM facility guidance through specific recommendations relating to aerosol science for a period of five years. The AMSG primary focus of this workshop was to help advance strategic external partnership engagement for ARM's aerosol measurement program. The workshop was held July 9-10, 2024 at the University of Utah. This was the third such workshop since the AMSG was chartered in 2015 to enhance coordination of ARM observations of aerosols and atmospheric trace gases with the needs of ARM users.

The focus of the 2024 workshop reflects the AMSG's focus in recent years on building external relationships between ARM and strategic partners who will contribute to the success of ARM to fulfill its mission of improving process representations and predictability in climate models. Sessions held during the workshop range from interfacing with external sampling networks and modeling communities through identifying core and new aerosol measurements, and providing a clear presentation of measurement uncertainties, calibration protocols, and data products.

The AMSG strategic planning workshops are designed to recommend actions that will enable ARM to evolve and continue to meet its mission. As part of this report, AMSG has developed a list of recommendations for ARM consisting of actionable items built from the discussions and compiled recommendations from the workshop. After the workshop, a survey was sent to the AMSG committee, which allowed for prioritization of these recommended actions, as indicated below.

The following recommendations are described in detail within this workshop report.

High-priority recommendations requiring immediate action are as follows:

Strengthen Partnerships and Coordination

- Motivate outside partners to use ARM data via strategic data sharing via widely used data portals. Recommend a new hire responsible for outreach and coordination with other international scientific networks.
- Continue and expand partnerships with the National Oceanic and Atmospheric Administration (NOAA)'s Federated Aerosol Network (FAN), the Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT), the pan-European Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS), the Interagency Monitoring of Protected Visual Environments (IMPROVE), the National Ecological Observatory Network (NEON), AmeriFlux, and other networks, including guest instrumentation and integration.
- Continuing progress on the Center for Aerosol Measurement Science (CAMS) and the standardization efforts of Cooperation and AgReements enhancing Global interOperability for Aerosol, Cloud and Trace gas research infrastructures (CARGO-ACT). Serve as leader for CARGO-ACT.

- Continue to use and support the Small Business Innovation Research (SBIR) and related Small Business Technology Transfer (STTR) programs to develop new instruments and techniques. Encourage SBIR/STTR principal investigators (PIs) to attend the ARM/Atmospheric System Research (ASR) PI meeting.
- Minimize the barriers between instrument mentors and modelers (e.g., improve refined searches on ARM Data Discovery).

Improve Data Accessibility

- Address key challenges including fragmented data quality reporting, inconsistent documentation, and limited mentor resources for user support. Expand outreach on how to best communicate uncertainties within data sets.
- Build creative deployment, modeling, and data-product development strategies to better integrate measurements over larger spatial and temporal scales.
- Focus on the application of machine learning models for rapidly identifying aerosol source profiles and providing automated QA/QC of data sets.

Advance Instrumentation, Platforms, and Emerging Techniques

- Uncrewed aerial system (UAS) and tethered balloon system (TBS) newly developed platforms are successfully characterizing vertical profiles, and require new instrument packages focusing on volatile organic compound (VOC) concentrations, gas and particle fluxes, and climatically relevant aerosol properties.

Additional priorities include:

Expand and Improve Core Aerosol Measurements

- Focus on aerosol coarse-mode measurements, while carefully considering sampling losses, with a focus on ice nucleating particle (INP) measurements.
- Implementing routine measurements of black carbon and VOCs at all sites.
- Prioritize measurements of aerosol hygroscopicity (in sub- and supersaturated conditions), with a focus below $d < 50$ nm, to provide composition information.
- Move towards size-resolved measurements of INP, cloud condensation nuclei concentration (CCNC), and black carbon (BC) measurements.
- Consider the role of low-cost sensors for capturing spatial heterogeneity and determine what level of uncertainty is acceptable relative to state-of-the-art techniques.
- Create a prioritized set of compact, (near) autonomous atmospheric and aerosol instruments that can be deployed in a spatially distributed network around an observatory.
- Prioritize up-and-coming aerosol instrumentation for offline and single-particle analyses (including physical, chemical, and climate-related properties, such as ultra-high-resolution mass spectrometers, chemically resolved imaging, and measurements of ice nucleation [IN] and cloud condensation nuclei [CCN] activity on individual particles).

- Continue to invest in autonomous (e.g., marine) and spatially distributed measurements, including new lower-cost condensation particle counters (CPCs) and scanning mobility particle sizer (SMPS) systems for mini- and micro-Aerosol Observing System (AOS) platforms, and expand these nodes to include optical properties, CCN, INP, trace gases, and potentially more.
- Develop, mature, and deploy ambient aerosol measurements alongside dry measurements to reconcile in situ and remote-sensing measurements and better quantify the role of aerosol water in particle size and optical properties.

Improve Data Product

- A new value-added product (VAP) that includes a retrieval of aerosol size distributions from lidars.

All planning documents and workshop presentations from the AMSG strategic planning workshop are organized and archived at this internet address (https://atmos.utah.edu/amsg_workshop/).

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACI	aerosol-cloud interactions
ACSM	aerosol chemical speciation monitor
ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
ADC	ARM Data Center
AeroCom	Aerosol Comparisons between Observations and Models
AERONET	Aerosol Robotic Network
AGL	above ground level
AGU	American Geophysical Union
AMF	ARM Mobile Facility
AMS	American Meteorological Society
AMSG	Aerosol Measurement Science Group
AOD	aerosol optical depth
AOS	Aerosol Observing System
API	Application Programming Interface
APS	aerodynamic particle sizer
ARM	Atmospheric Radiation Measurement
ASCENT	Atmospheric Science and Chemistry mEasurement NeTwork
ASR	Atmospheric System Research
BAMS	*Bulletin of the American Meteorological Society*
BC	black carbon
BNF	Bankhead National Forest
BNL	Brookhaven National Laboratory
CAMS	Center for Aerosol Measurement Science
CARGO-ACT	Cooperation and AgReements enhancing Global interOperability for Aerosol, Cloud and Trace gas research infrastructures
CCN	cloud condensation nuclei
CCNC	cloud condensation nuclei counter or cloud condensation nuclei concentration
CDCE	composition-dependent collection efficiency
CF	Community Foundation
CoURAGE	Coast-Urban-Rural Atmospheric Gradient Experiment
CPC	condensation particle counter
CRG	CoURAGE site code
DMA	differential mobility analyzer
DOE	U.S. Department of Energy

DOI	Digital Object Identifier
DQ	data quality
DQO	Data Quality Office
E3SM	Energy Exascale Earth System Model
EMSL	Environmental Molecular Sciences Laboratory
ENA	Eastern North Atlantic
EOL	Earth Observing Laboratory
EPA	Environmental Protection Agency
EPCAPE	Eastern Pacific Cloud Aerosol Precipitation Experiment
ESMAC_diag	Earth System Model Aerosol-Cloud diagnostic
FAN	Federated Aerosol Network
FAQ	frequently asked question
GASSP	Global Aerosol Synthesis and Science Project
GAW	Global Atmosphere Watch
GML	Global Monitoring Laboratory
HPC	High-Performance Computing
HSRL	high-spectral-resolution lidar
HTDMA	humidified tandem differential mobility analyzer
IMPROVE	Interagency Monitoring of Protected Visual Environments
IN	ice nucleation
INP	ice nucleating particle
IOP	intensive operational period
LaRC	Langley Research Center
LIDARAEROMASK	Aerosol Feature Mask Value-Added Product
LLOD	lower limit of detection
LOTOS	Lower Troposphere Observing System
LWP	liquid water path
MACIE	Measurements of Aerosols, Clouds and their Interaction for Earth Systems Models
MFRSR	multifilter rotating shadowband radiometer
ML	machine learning
MPL	micropulse lidar
MSL	mean sea level
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
Nd	cloud droplet number
NEON	National Ecological Observatory Network
NetCDF	Network Common Data Form

NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
OPC	optical particle counter
OSSE	Observing System Simulation Experiment
PASS	photo acoustic soot spectrometer
PI	principal investigator
PMF	Positive Matrix Factorization
PNNL	Pacific Northwest National Laboratory
POPS	portable optical particle spectrometer
PSAP	particle soot absorption photometer
PTR-MS	proton transfer reaction mass spectrometer
QA	quality assurance
QC	quality control
RH	relative humidity
RL	Raman lidar
SBIR	Small Business Innovation Research
Science RoCS	Science Research on Commercial Ships
SGP	Southern Great Plains
SMPS	scanning mobility particle sizer
SP2	single-particle soot photometer
STTR	Small Business Technology Transfer
TBS	tethered balloon system
TRACER	Tracking Aerosol Convection Interaction Experiment
UAS	uncrewed aerial system
USDA	U.S. Department of Agriculture
UV-B	ultraviolet-B
VAP	value-added product
VOC	volatile organic compound
WMO	World Meteorological Organization

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1.0 Introduction

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility chartered the Aerosol Measurement Science Group (AMSG) in 2015 as a constituent group tasked with providing enhanced coordination of ARM observations of aerosols and atmospheric trace gases with the needs of its users (https://www.arm.gov/about/constituent-groups/amsg). To help guide ARM, the AMSG has organized several strategic planning workshops to obtain input from within ARM and external scientific communities and recorded the resulting recommendations in published ARM reports.

The first AMSG strategic planning workshop was held in 2017 to delineate specific instrumentation, measurements, and data-product development efforts for ARM observatories and mobile sites and to consider physical system configurations that impact the nature and quality of observables. Topics involving calibration strategies and overarching deployment strategies for Aerosol Observing Systems (AOS) were briefly discussed, and the need to improve communication about and accessibility of data in the ARM Data Center (ADC) emerged as a theme. The latter point was considered a significant obstacle to increasing data usage. From the outcomes of the 2017 workshop (McComiskey and Sisterson, 2018), an objective implementation plan with well-defined deliverables was developed. Significant progress has been made in fulfilling these deliverables, resulting in a more comprehensive, higher-quality, and easier-to-access set of aerosol measurements available in the ADC.

In subsequent years, as technical progress was being made on measurement and physical systems, the focus of the AMSG has turned to science-based strategies that will contribute to the increased use of ARM data to fulfill its mission of improving process representations and predictability in climate models. Decisions regarding sampling strategy, data presentation, and engagement with the external community play at least a comparable role to technical instrument and measurement issues in the impact ARM measurements have on advancing atmospheric process understanding and the fidelity of climate models, serving the needs of the Atmospheric Systems Research (ASR) and Energy Exascale Earth System Model (E3SM) programs.

The second AMSG strategic planning workshop was held in November 2019 to advance a science-based strategy for ARM's aerosol measurement program. The results of the second workshop reflected AMSG's focus on science-based strategies that will contribute to the increased use of ARM data to fulfill its mission of improving process representations and predictability in climate models. During the second workshop four areas emerged as priorities 1) aerosol measurements on the North Slope of Alaska, 2) improving data usability for modeling, 3) strategies for advancing remote sensing, vertical profiling, and distributed measurements of aerosols, and 4) aerosol sampling strategies at existing ARM sites to provide intensive modes of operation to promote data usage for process and modeling studies.

After the second workshop, the AMSG recommended that ARM generate and publish an annual Aerosol Operations Plan (AOP) to detail status on ARM aerosol-related topics. There have been three (FY24, FY25, and FY26) ARM AOPs published, which can be found on DOE ARM's websites (Theisen et al. 2023, Mayol-Bracero et al. 2025a, 2025b). These annual reports include:

- Data Products: Details on the collection, processing, and dissemination of aerosol data.

- Value-added products (VAPs): Enhancements to raw data to make them more useful for scientific analysis.
- Instrumentation: Updates on aerosol measurement instruments and their deployment.
- Research Goals: Objectives for understanding aerosol properties and their impact on climate and atmospheric processes.

The third AMSG strategic planning workshop, the topic of this report, was recently hosted by the University of Utah in the summer of 2024. The workshop was held from July 9-10 in Salt Lake City at the University of Utah's Alumni House. The focus of the 2024 workshop reflects AMSG's focus in recent years on building external relationships between ARM and strategic partners that will contribute to the success of ARM in fulfilling its mission of improving process representations and predictability in climate models. Sessions held during the workshop range from interfacing with external sampling networks and modeling communities through identifying core and new aerosol measurements, and providing a clear presentation of measurement uncertainties, calibration protocols, and data products.

The purpose of the third AMSG strategic planning workshop, and this resulting report, is to provide scientific community input relevant to ARM user facility strategic planning for the next five-year timeframe.

2.0 Workshop Focus

The main focus of the current (i.e., third) AMSG strategic planning workshop is how ARM can benefit by actively engaging with strategic partners. This AMSG workshop was designed to generate a list of recommended actions that will enable ARM to evolve and continue to meet its mission over the next five years. Before the workshop, the AMSG committee engaged with the community via breakout sessions at the annual ARM/ASR PI meeting. Via this engagement, and quarterly meetings of the AMSG Committee, a list of target areas was developed for this workshop. A set of presentation and reporting guidelines was drafted to help ensure uniformity in presentations/reporting for each target area. Each topic was assigned a leader to create a breakout session for the workshop. Finally, three well-respected scientists were invited to give presentations to help inform and guide the workshop discussions.

2.1 Plenary Presentation

Benefits of Engagement with External Strategic Partnerships

Professor Paolo Laj, Head of the Global Atmosphere Watch (GAW) Programme at the Science and Innovation Department of the World Meteorological Organization (WMO), presented on the benefits of engagement with external strategic partners. Despite the crucial importance of aerosols as short-lived climate forcers, specifically with respect to aerosol-cloud interactions (ACI), and their importance for air quality, monitoring networks are lacking in global, coordinated coverage. The current lack of overlap between models and observations is a concern, with most models using aerosol optical depth (AOD) as an observation reference, even though it is not a strong constraint. Few aerosol measurements are available to compare with models. Regional cooperation between the U.S. and Europe is needed for global cooperation.

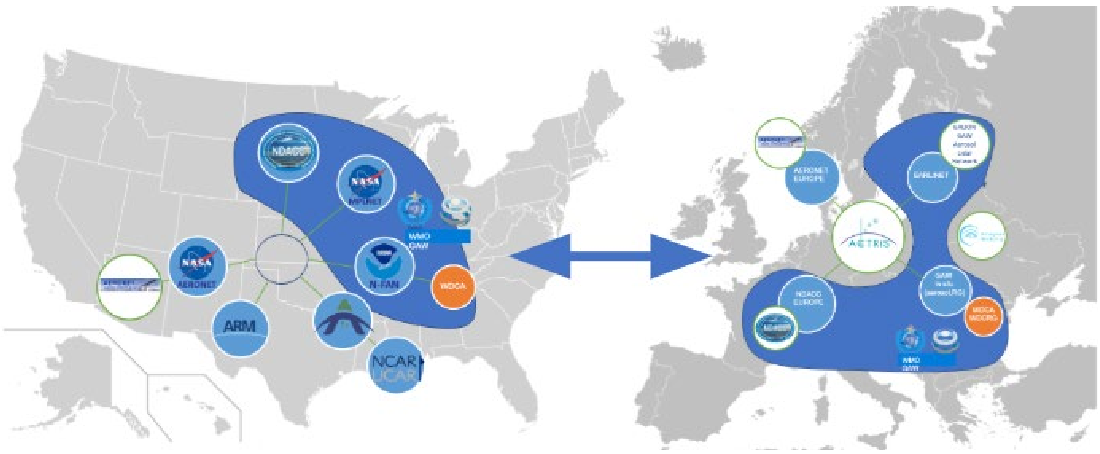

Figure 1. Strategic network partnerships.

2.2 Workshop Target Areas

Prior to the workshop, the target area leads developed concise introductions to their breakout session topics, including relevant background material, and generated starter lists of opportunities and roadblocks. Several breakout sessions included presentations from either the leads or other attendees. During the session, the group brainstormed (a) strategic opportunities and (b) problematic roadblocks for ARM relating to their session topic. The leaders documented and prioritized actionable items relating to how ARM can take advantage of opportunities and address roadblocks within the framework of a five-year strategic plan. The group then worked together to sort actionable items by (a) timescale and (b) resources required. The results from this breakout were then summarized on Day 2 through lightning presentations by the breakout leads, which formed the basis for this workshop report. Specifically, the workshop focused on the following list of topics, with the leadership listed for each topic.

AMSG Workshop Target Areas

1. Core aerosol-related measurements (John Shilling/Lynn Russell)
   - Size distributions, hygroscopicity, CCN/IN, chemistry, online VOC measurements, trace gas measurements
   - Offline VOC measurements
   - Where/when are these measurements most necessary? (24-7 versus intensive operational period [IOP])
2. Engage with strategic partners (Gannet Hallar/Tim Onasch)
   - Including both domestic and international partnerships
   - Environmental justice
3. Improving the understanding and accessibility of ARM aerosol data (Adam Thiesen/Alyssa Sockol)
   - Generate ARM technical reports
   - Publish technical papers (specifically relevant to ARM reports)

- Reporting and reprocessing workflows

4. New aerosol measurement techniques (Jim Smith/Markus Petters)
   - Measurements
   - Analysis – including machine learning
5. Measurement uncertainties (Olga Mayol-Bracero/Rich Moore)
   - Calibrations, closure studies, etc.
   - Center for Aerosol Measurement Science
6. Roadmap to modeling (Jerome Fast/Nicole Riemer)
   - Outreach to AeroCom/AeroSat Global Modeling community
   - Data availability, data uncertainty, metadata information
   - ARM facilities provide "core" or "baseline" measurements for direct inclusion in E3SM
7. Large spatial and temporal science studies (Chongai Kuang/Damao Zhang)
   - "The best of DOE science"
   - ARM facilities at the center of national and international campaigns
   - Horizontal and vertical spatiotemporal coverage
   - Aerosols near cloud base needed for aerosol-cloud interactions
   - Clean versus "dirty", rural versus urban
   - Coarse-mode aerosol.

2.3 Cross-Cutting Sessions

In addition to the seven breakout sessions held on the first day (July 9, 2024) of the workshop, the second day (July 10, 2024) started with lightning talks summarizing the discussions from each breakout session. The remainder of the second day included two cross-cutting sessions, highlighted by invited keynote presentations by Dr. Andrews (NOAA) and Dr. McComiskey (NCAR), and a work session focused on collecting and summarizing results. Finally, on the morning of the third day (July 11, 2024), a small group of participants met to start writing the report.

Improve Existing ARM Systems and Programs — The Multiplying Effect of Working Together

Dr. Elizabeth (Betsy) Andrews, CERES Research Scientist at the National Oceanographic and Atmospheric Administration (NOAA) Global Monitoring Laboratory (GML) and the University of Colorado, presented on the challenges of establishing long-term aerosol monitoring systems and programs due to the variability of aerosols from different locations. The NOAA Federated Aerosol Network (FAN), which has 32 sites, has been established to provide comparable measurements to those made in Europe, through the ACTRIS program. The presentation highlighted the advantages of long-term cooperation with other institutions, such as instrument loans, shared expertise, independent site audits, and operational advantages such as co-location at existing sites, shared infrastructure, and instrument data. Dr. Andrews also discussed the challenges of data harmonization from different data sources, including the need for a standard web service Application Programming Interface (API) for data submission.

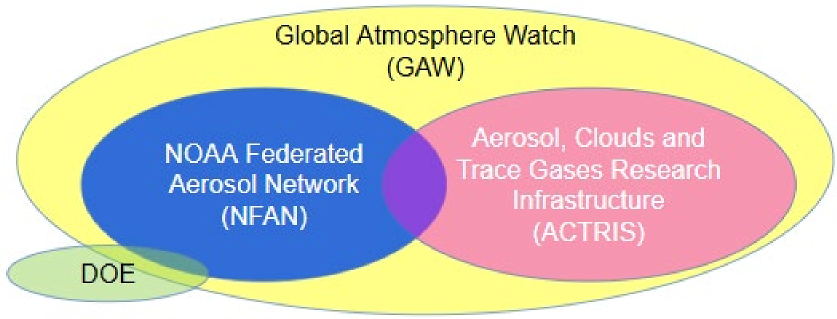

Figure 2. Collaboration between institutions can improve existing aerosol monitoring systems and programs.

New Frontiers of ARM

Dr. Allison McComiskey, the Director of the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL), highlighted the complexity of climate change, including the impact of meteorological and aerosol impacts on clouds, and our ability to measure, model, and predict future changes. Dr. McComiskey stressed the need to bridge scales and model closure from observational systems, using a proposed LOwer Troposphere Observing System (LOTOS) distributed network as an example. The presentation discussed strategic opportunities, error characterization, and roadblocks in advancing predictions. The presentation also included the need for data accessibility, including observational and model data.

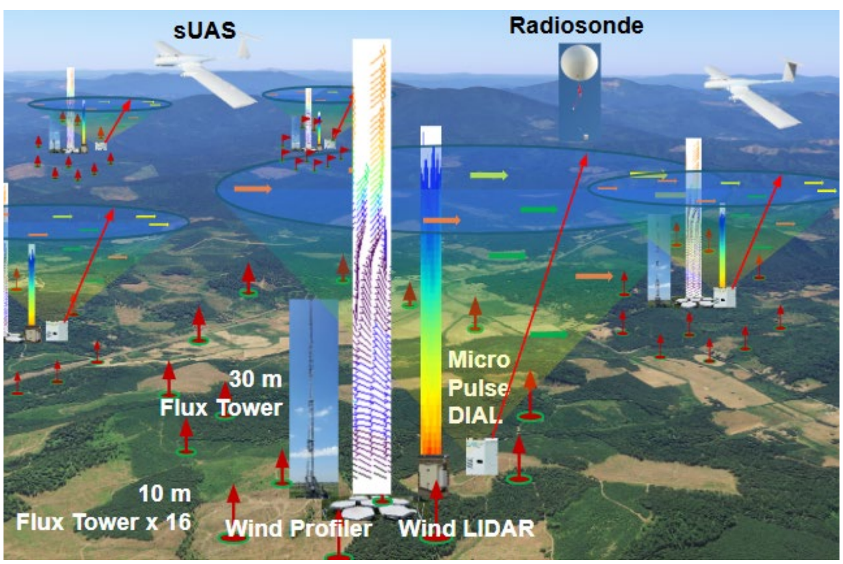

Figure 3. A visualization of a potential deployment of the NCAR EOL LOTOS network sampling the boundary layer across a heterogeneous domain.

3.0 Breakout Sessions

Each breakout session was organized individually by a team of leads, based on a common guideline for discussions and reporting. All seven breakout sessions were held during the first workshop day (July 9, 2024), during three 1:30 periods, with overlapping sessions of two or three during each period. The breakout sessions were live-streamed on Zoom and recorded.

As part of the workshop, each breakout team was requested to provide a report chapter using the following guide:

Overview

– What was the purpose of the session and why was it formatted in this way?
– What were the presentations?

Capabilities

– If relevant, state what is currently being done in this area.

Opportunities

– Where are the opportunities for ARM?

Roadblocks

– What are the challenges that must be addressed?

Concluding Remarks

– The last paragraph should emphasize some of the takeaways from the session.

3.1 Core Aerosol-Related Measurements

Organizers: John Shilling, Lynn Russell

3.1.1 Overview

This session focused on reviewing the core aerosol measurements that are made as part of ARM's Aerosol Observing System (AOS). Olga Mayol-Bracero presented an overview of the baseline instrumentation that is currently deployed in the ARM Mobile Facilities (AMFs). John Shilling presented an overview of current and planned aerosol-related VAPS. The planned operational mode of the instrumentation (IOP-mode versus 24/7 operations) was also discussed.

3.1.2 Capabilities

The AMF instrument complement at the time of the workshop discussion is shown in the table below. Updated AMF instrument complements are available in the annual Aerosol Operations Plan.

Table 1. ARM Mobile Facility instruments at the time of the workshop.

Instrument	AMF1	AMF2	AMF3	SGP	ENA	NSA	IOP
Aerosol Chemical Speciation Monitor - Quadruprole (ACSM)							
Aerosol Chemical Speciation Monitor - Time of Flight (ACSMTOF)							
Aethalometer (AETH)						NOAA	
Aerodynamic Particle Sizer (APS)							
Cavity Attenuated Phase Shift Monitor (CAPS)							
Carbon Monoxide/Nitrous Oxide/Water Vapor (CO)							
Continuous Light Absorption Photometer						NOAA	
Cloud Condensation Nuclei (CCN)							
Condensation Particle Counter (CPC, CPCF)						NOAA	
Ultrafine Condensation Particle Counter (CPCUF, CPCU)							
Humidified Tandem Differential Mobility Analyzer (HTDMA)							
Impactor (1-10 μm)						NOAA	
Nano Scanning Mobility Particle Sizer (NANOSMPS)							
Nephelometer, Ambient (NEPHDRY)						NOAA	
Nephelometer, RH Scanned (NEPHWET)							
Humidigraph							
Ozone (OZONE)							
Scanning Mobility Particle Sizer (SMPS)							
Sulfur Dioxide (SO2)							
Single Particle Soot Photometer (SP2)	IOP	IOP	XR			XR	X
Ultra High Sensitivity Aerosol Spectrometer (UHSAS)							
Meteorological Information (AOSMET)							
Filters for Ice Nucleating Particles (INS/INP)		IOP					
Proton Transfer Reaction Mass Spectrometer (PTRMS)							X
Nitrogen Oxide 3 Channel [NO, NO2, NOy] (NOX)							X
GreenHouse Gases [CO2, CH4] (GHG)							X
Planned additions in FY24							
Planned Removals							

3.1.3 Opportunities and Roadblocks

3.1.3.1 Instrument Needs

Changes to existing instrument operations

Currently, ARM capabilities are best suited to measurements of particles smaller than approximately 1 μm. There are fewer measurements of the aerosol coarse mode (particles > 1 μm in diameter). The coarse-mode aerosol may be important for understanding a number of science questions including aerosol optical properties. The core coarse-mode measurement in the AOS system is the aerodynamic particle sizer (APS), which measures particles up to approximately 20 um. However, the APS and any instruments that measure coarse-mode aerosol are limited by the difficulty of sampling and transmitting coarse-mode particles through aerosol inlet, associated tubing, and into the instrument. The group recommends that ARM investigate additional strategies for reducing loss of coarse-mode aerosol. One strategy could be to bypass the typical inlet structure for a more direct path into the APS. Another strategy would be to retrieve dust and coarse mode from remote-sensing measurements, which is currently being explored by the ARM data analysts.

The importance of continuing measurements made by humidified tandem differential mobility analyzer (HTDMA) was discussed. This instrument is the only core ARM instrument capable of inferring information about the size-dependent chemical composition of particles. This instrument is difficult to run operationally; however, the group felt it was valuable to continue measurements. This instrument is most useful for investigating the composition of smaller particles; therefore, the group recommends that ARM make HTDMA measurements at $d < 50$ nm. This could be accomplished by either adding measurement(s) of smaller diameters into the scanned diameters and decreasing the time resolution or by eliminating a measurement at a larger diameter.

The use of INP data was also discussed and a recommendation was made that INP measurements be focused on campaigns and regions where mixed-phase clouds are climatically important. In particular, this would mean focusing efforts on ARM's North Slope of Alaska (NSA) site or future field deployments with mixed-phase clouds. The group also noted that data would be more useful if the sampling were conducted behind a differential mobility analyzer (DMA). Finally, there was strong general support for moving more instruments behind a DMA, including a future BC measurement, INP collection, and potentially the CCN instrument.

3.1.3.2 New Measurement Needs

The group discussed the in situ measurements of aerosol optical properties currently being made by ARM using the particle soot absorption photometer (PSAP). The PSAP is discontinued by the manufacturer and supporting the instrument is becoming difficult as spare parts are becoming difficult to purchase. The group acknowledged that filter-based measurements have large uncertainties associated with measurements of aerosol absorption. However, currently available commercial instruments that measure suspended aerosol optical properties have poor detection limits that are often higher than ambient values. No conclusion was reached regarding whether ARM should use an aethelometer (filter-based measurement) as a stop-gap or try to implement an instrument that measures suspended particles. The group noted that past attempts to measure aerosol absorption with the photo acoustic soot spectrometer (PASS) by ARM were unsuccessful.

We also recommended that ARM consider implementing two new measurements, one of black carbon and another of VOCs. Development of a new instrument, the single-particle soot photometer (SP2-XR), may allow for routine monitoring of BC with much less data-processing time necessary to reduce the data to geophysical units. If ARM moves forward, we recommend they consider operating the instrument behind a DMA to obtain information about the thickness of coatings on BC particles. The group also reiterated the need for VOC measurements, particularly during IOPs. ARM has previously attempted to operate a proton transfer reaction mass spectrometer (PTR-MS) for this purpose during IOPs, but operations were discontinued primarily due to cost. Here again advances in instrumentation may make these measurements more routine and less costly. Alternatively, the group recommends that ARM explore the cost and difficulty of canister sampling for VOC analysis.

3.1.3.3 Data Product Needs

Existing Data Products

After discussion of instrumentation needs, we moved on to a discussion of data products needed to improve data usage. We began with a discussion of the QA/QC labeling of the merged size distribution VAP. Data that may be of adequate quality for some purposes (e.g., global modeling) may not be suitable for more detailed analyses. Currently, poor-quality data is flagged rather than removed and the group generally agreed that this was the best compromise between different data quality needs. The group discussed the aerosol chemical speciation monitor (ACSM) composition-dependent collection efficiency (CDCE) and generally agreed that the data are generally well characterized; however, there is limited literature validation of the CDCE algorithm for marine environments. We recommend that a data quality (DQ) report be generated when the ACSM operates in marine environments explaining this limitation.

New Data Product Needs

Recognizing the need for more information regarding the vertical distribution of aerosol, the group discussed the potential for retrievals of the aerosol properties from remote-sensing instrumentation, particularly the ARM lidars. We recommend that DOE consider retrieving the aerosol size distribution from these measurements. It was noted that such a retrieval may be underway by the data analyst group and we recommend ARM continue to support development and refinement of this VAP. Such a retrieval would also provide an additional constraint on the coarse-mode aerosol population. The group also discussed the possibility of releasing Positive Matrix Factorization (PMF) analysis of the ACSM data. There was recognition that this is labor-intensive and expensive, and that the proprietary nature of the PMF algorithm makes it somewhat contrary to ARM's operational model. The group pointed out that alternatives to PMF would serve the same function and ARM may want to explore these options. Finally, there was a discussion of the need for a merged aerosol data product that would combine information from multiple measurements into a single file on a common time-base.

3.1.4 Concluding Remarks

ARM should enhance its aerosol measurement capabilities by improving coarse-mode aerosol sampling and by continuing HTDMA operations focused on particles smaller than 50 nm to retain chemical composition data. INP measurements should be prioritized. ARM should enable more size-selected measurements behind a DMA, including a BC measurement, INP collection, and CCN activation. The group also recommends addressing the discontinuation of the PSAP by evaluating replacement options, such as an aethalometer or instruments measuring suspended aerosols. New measurements are encouraged for black carbon using the emerging SP2-XR (ideally operated behind a DMA) and for VOCs, either through renewed PTR-MS deployment or cost-effective canister sampling.

3.2 Engage with Strategic Partners

Organizers: Gannet Hallar, Tim Onasch

3.2.1 Overview

ARM's current capabilities include long-term fixed observatories, mobile and aerial facilities, and continuous measurement systems. ARM supports several different measurement "sites" (including fixed and mobile, airborne, and shipborne) and stands out in the sheer number of instruments per site, but also in the limited number of sites (refer to Figure 4). In contrast, much of today's aerosol science relies on short-term, process-specific studies. Strengthening ARM's relevance and scientific impact will depend on strategic partnerships that expand collaboration, enhance data accessibility, and align measurement strategies with broader community needs.

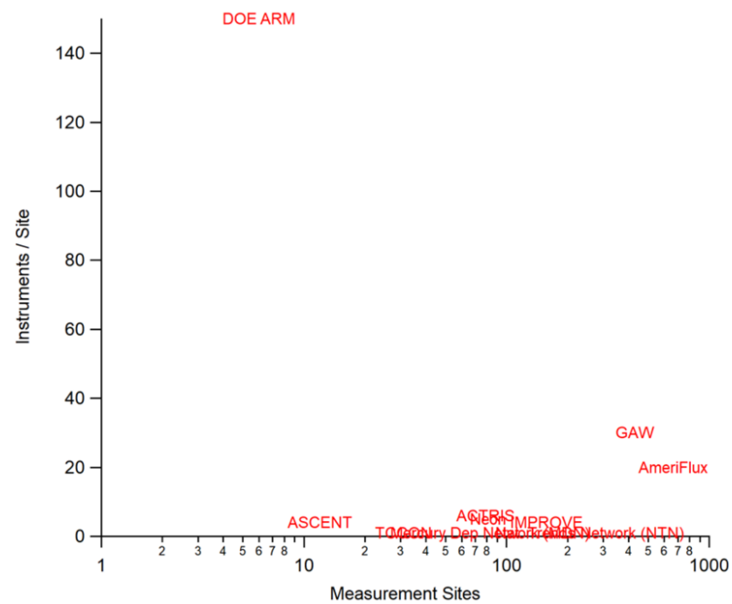

Figure 4. Scatter plot highlighting ARM's unique capabilities of deploying highly instrumentation field sites.

3.2.2 Capabilities

ARM currently supports long-term observatories or fixed sites, mobile facilities, and multiple aerial facilities (crewed and uncrewed aircraft and tethered balloons). Much effort has gone into determining the suite of measurements that comprise the AOS at each of these facilities, which are very similar for each site and run continuously at fixed sites and throughout campaigns. However, much of current aerosol science is process-specific and investigated through short-term IOP studies. Further, many tend to be bulk measurements that equate to larger spatial and temporal scales and do not necessarily address the details required for model advancement.

Session members recognized that partnerships may enhance the ability of ARM to support the most relevant science being pursued by the community in the long term and enhance the science that can be done with the current ARM measurement strategy immediately. Recommendations from this session are listed here pertaining to partnership methods.

3.2.3 Opportunities

The strategy should focus on expanding engagement with strategic partners by re-establishing and continuing relationships with organizations like FAN and ASCENT. We suggest starting with one key partnership to demonstrate success before scaling up. Collaboration among agencies is encouraged to improve coordination on campaigns, with active participation in the European CARGO-ACT project. ARM should act as the U.S. leader in the CARGO-ACT project to connect our nation's networks more effectively. Efforts should focus on understanding the motivations of external partners and how best to "sell" ARM to the broader community, beginning with influential modelers or users who can act as peer champions. Additional outreach may include engaging with big data firms, learning from the air quality network, and drawing lessons from successful initiatives like ACTRIS and other environmental science collaborations.

The community outreach strategy should emphasize increasing visibility and engagement with external partners by highlighting existing collaborations—such as featuring them on the ARM "About" webpage, where current partnerships outside DOE are not yet acknowledged. It should also include showcasing ARM's collaborative processes, for example, through an aerosol-focused *Bulletin of the American Meteorological Society* (BAMS) paper. A "customer discovery" or "community engagement" model may be useful to better understand community needs. Additionally, we encourage broader participation by partners at ARM/ASR PI meetings, including other federal agencies. The outreach strategy could include a breakout session at the ARM/ASR PI meeting centered on collaboration. Finally, increasing the involvement of SBIR winners and private companies at the annual meeting would be beneficial.

The network measurement strategy should focus on strengthening and expanding ARM's integration with other observational networks to enhance measurement scope, data quality, and scientific collaboration. This includes continuing to incorporate ARM ground sites—such as IMPROVE at the Southern Great Plains (SGP) observatory—into external networks and exploring similar integration at additional locations. Connections with other efforts, like the U.S. Department of Agriculture (USDA) ultraviolet-B (UV-B) network at Colorado State University, will help link complementary measurement systems (e.g., using multifilter rotating shadowband radiometer [MFRSR] sensors).

ARM should continue supporting Brookhaven National Laboratory (BNL) Center for Aerosol Measurement Science (CAMS), an exceptional international collaboration, that will allow both DOE and external sites to ensure compatibility, calibrations, and maximize scientific value. The approach should consider models like the Aerosol Robotic Network (AERONET), which emphasize dense site coverage with fewer instruments, and proposes adding ASCENT to ARM sites once National Science Foundation support ends. By embedding ARM sites in external networks, IOPs and modeling infrastructure naturally extend across multiple networks, fostering broader data sharing and collaboration.

Long-term coordination should also focus on attracting additional research groups to ARM sites, improving site selection, and ensuring that surface measurements accurately represent atmospheric column conditions—potentially through innovations such as elevated inlets to capture measurements above the surface layer.

Efforts are needed to determine whether standardizing ARM data files would improve their accessibility and use by other research networks. If standardization is necessary, dedicated ARM resources must be allocated, though this would be a nontrivial effort. The benefits include increased visibility and broader collaboration.

ARM should also focus on reducing acronyms to promote inclusivity and explore joint data portals to encourage cultural shifts—so that researchers from NASA, NOAA, and other agencies also use ARM data. We recommend leveraging the versatility of ARM's core data and its extensive measurements as a unique strength. Examples like Global Aerosol Synthesis and Science Project (GASSP) aircraft collaborations highlight opportunities for cross-network engagement. Data quality and timeliness tend to improve with external use, and offering data bundles or conversions (e.g., from rapid 1 Hz ARM data to hourly GAW-format averages) could make data more accessible while keeping control within ARM's systems (e.g., Data Discovery). Continued investment in interagency standardization efforts, such as the Measurements of Aerosols, Clouds and their Interaction for Earth Systems Models (MACIE) initiative, common naming conventions, and NetCDF formats, is essential. Collaboration through groups like CARGO-ACT and the integration of campaign aircraft data into unified NetCDF files (as in ARM Aerial Facility [AAF]merge) demonstrate successful progress toward these goals.

3.2.4 Roadblocks

Engaging effectively with strategic partners requires addressing several challenges, including funding constraints, interagency politics, and misaligned incentives that discourage collaboration across organizations. Coordination between agencies—each with distinct research goals and measurement approaches—can be hindered by competing efforts and limited resources. Even small-scale coordination demands dedicated effort, suggesting the need for a point person or team to lead outreach and assess its effectiveness. ARM should consider a new hire, whose focus is responsibility for outreach/coordination focused on other networks. Outreach could be initiated through venues like American Geophysical Union (AGU) and American Meteorological Society (AMS) booths or town halls.

On the infrastructure side, a limited number of ARM sites constrain incorporation into broader network measurements. Yet, it will be critical to stress the importance of the number and depth of measurements at each site, especially as the data sets expand into multi-decadal.

For data accessibility and sharing, ARM must set a high standard for data quality and transparency, ensuring documentation clearly conveys uncertainties and the relationship between VAPs and raw measurements. Establishing fair credit practices is also essential, as it can be difficult to attribute data contributions across multiple sources without weakening credibility. Demonstrating the value of shared, high-quality data—both scientifically and in terms of accountability—will be key to convincing policymakers and funders of the importance of interagency collaboration.

3.2.5 Concluding Remarks

The proposed strategy emphasizes re-establishing and strengthening partnerships with groups like FAN and ASCENT, active leadership in international efforts such as CARGO-ACT, and engagement with influential modelers, agencies, and private companies to build visibility and trust. Outreach efforts should showcase existing collaborations, improve interagency coordination, and promote ARM's integration with external networks (e.g., IMPROVE, AERONET, USDA UV-B, Environmental Protection Agency [EPA] AirNow, etc.) to enhance measurement scope, calibration, and data interoperability. Standardizing data formats, improving documentation, and developing data bundles could make ARM data sets more accessible while maintaining quality and control. However, challenges remain, including funding limitations, agency politics, and misaligned incentives that slow coordination. One step forward in addressing these challenges is a dedicated outreach lead or team to sustain partnerships, strengthen interagency culture, and communicate ARM's scientific value to outside stakeholders. Expanding network integration, ensuring representativeness of site measurements, and maintaining exemplary data quality and transparency will be crucial for ARM to serve as a model for collaborative, high-impact atmospheric research.

3.3 Improving the Understanding and Accessibility of ARM Aerosol Data

Organizers: Adam Thiesen, Alyssa Sockol

3.3.1 Overview

ARM is continually trying to improve the understanding and accessibility of its data as a whole. This session focused on areas that have previously been reported to ARM as areas of improvements through previous ARM surveys and user engagement. These topics include identifying future directions for technical reports, new calibration system capabilities, accessing information on ARM instrumentation, data quality information, and identifying gaps in aerosol data information, organization, and understanding. This session had limited attendance with three attendees either being current or previous ARM mentors and one member from the science community. It will be important for continued engagement with the aerosol community on these topics to ensure a broad spectrum of opinions are further incorporated.

ARM has made significant efforts to better inform the user community of activities and priorities through the yearly Aerosol Operations Plan (Theisen et al. 2023). Information specific to the configuration of the AOS is available through the ARM AOS Overview Paper (Uin et al. 2019) and even more information is planned to be published through technical reports such as a report on UHSAS artifacts. There are also reports on mentor and engineering activities that are kept internal to ARM for various reasons; scope of activity, effort to publish, etc. All this information and more is available through ARM's instrument webpages.

In response to the 2020 DOE Triennial Review, ARM is in the process of developing a new calibration system to better track calibration plans and timelines, record results, and disseminate this information to users. Plans and reports are flexible enough to be tailored to each instrument. The last phase of the calibration tool to disseminate information to data users is planned for late FY24 or early FY25. This will include providing information through Data Discovery in a manner similar to data quality reports (DQR), which are visible on the data timeline, delivered with data orders, and accessible through online tools and web services. These efforts will further provide confidence in ARM's quality of data.

Prior to the workshop, a survey was sent out to the participants to further steer discussion on ARM's data quality. Eighteen attendees responded to the survey which the questions are outlined in Table 1. Table 2 provides further input from the respondents on the challenges, requested improvements, and other thoughts of using ARM's data quality information. It should be noted that ARM does have mechanisms for users to report data quality issues back to ARM in a manner that is tracked by ARM staff through to resolution. This involves using the "Data Questions" link at the bottom of any ARM webpage.

Table 2. Summary of results of the DQ survey of AMSG workshop attendees.

Question	**1 - Frequent Very Effective Very Satisfied**	**2 - Few times Somewhat effective, satisfied**	**3 - Rarely Somewhat Ineffective, Unsatisfied**	**4 - Never Ineffective Unsatisfied**	**N/A**
How often do you work with ARM data?	83.3%	11.1%	5.6%	0%	0%
Please indicate your view of the effectiveness of Data Quality Reports (DQR)	22.2%	44.4%	11.1%	0%	22.2%
Please indicate your view of the effectiveness of embedded QC (qc variables in files)	44.4%	38.9%	0%	0%	16.7
Please indicate your view of the effectiveness of instrument handbooks	11.1%	50%	11.1%	0%	27.8%
Please indicate your view of the effectiveness of DQ Office Tools (DQ-Plotbrowser, DQ-Zoom)	16.7%	27.8%	5.5%	0%	50%
Overall, how satisfied are you with the communication of data quality information within ARM?	5.55%	61.1%	27.8%	0%	5.55%

Table 3. Additional feedback from AMSG workshop attendees.

What obstacles or challenges have you encountered when trying to access ARM data quality information?	**Are there specific features or functionalities you would like to see to improve the communication of data quality information?**	**Are there any thoughts you would like to share concerning the communication of data quality information that have not been covered in this survey?**
The DQ information is scattered over multiple sources (DQRs, DQ flags) and it is not always obvious to the user which set they should use or that there even is more than one set of information. Secondly, potentially compromised data is not excluded by default when ordering data through Data Discovery. A user needs to opt OUT of this data, which users often fail to do for one reason or another.	Single source of DQ information that is clearly advertised during data ordering process. Also, during data ordering, exclude potentially compromised data by default or better yet, do not make it available without a special request.	

What obstacles or challenges have you encountered when trying to access ARM data quality information?	**Are there specific features or functionalities you would like to see to improve the communication of data quality information?**	**Are there any thoughts you would like to share concerning the communication of data quality information that have not been covered in this survey?**
As a modeler, sometimes I am not sure if the data is accurate or if there is any inherent issue without a clear note.	More efficient visualization tool to directly check the observation data.	None
I have found some data issues that were not previously known or reported. ARM addressed them, but it was not an efficient process.	I'd request more responsiveness/prioritization when issues arise.	N/A
For some instruments (e.g., high-spectral-resolution lidar [HSRL]), there is no DQ information in the data files from ADC, or the DQ is not helpful (e.g., data does not look reasonable while DQ indicates good data).		
Not all the information and problems included.	Include raw data in next-level files (processed files).	
I hate having to merge DQR info with data files — I just want clean data files with suspect and invalid data already removed. It would make it SO much easier to work with the data. (Also lower-resolution data — [1min], 1sec data — is painful for anything I do.)	A 'clean' data file with all suspect and invalid data removed so consideration of DQRs is not necessary.	Access to handbooks (or handbook sections) for specific instruments rather than only one handbook for one type of CPC when there might be multiple CPC models used.
The main challenge is direct communications with the mentors when some suspicious data is found, and the way it is reprocessed.	It would be good to get notified when a datastream that you have downloaded previously is updated at the database.	
		It may just be personal preference, but I tend to use this website more than the DQ links above to visualize data and metadata before downloading it during an ongoing campaign — https://adc.arm.gov/afcd/#/. Are there plans to link these campaign sites to the DQ information or to let users know that newer, higher-quality data products might exist in ARM Data Discovery?

What obstacles or challenges have you encountered when trying to access ARM data quality information?	Are there specific features or functionalities you would like to see to improve the communication of data quality information?	Are there any thoughts you would like to share concerning the communication of data quality information that have not been covered in this survey?
There are certain data sets where I am not sure if a “weird”-looking feature is “real” or an instrument “artifact” and there is no clear guidance about how to either use, not use, or selectively use such data.		
The data quality flags can be a little difficult to interpret. Some bits are labeled as bad while others are labeled as intermediate and it's not always easy to understand whether the flagged data are usable or not. Some of the data quality reports are more detailed than others depending on the instrument and site. I have seen instances where the data look suspicious but there is no mention of these periods in the Data Quality Report, which has led us to need to reach out to the instrument mentor for clarification.	I think the DQRs could include more information, especially when the data are flagged. I have seen several data sets where much or all of the data are flagged, but there are no explanations for the flagged data in the DQRs. It would be helpful if the DQRs mention whether the flagged data are still usable or not.	
		We found a good set of aerosol measurement data but didn't find adequate data for aerosol precursors. I strongly recommend ARM to add instruments measuring key aerosol precursors (SO_2, NH_3, key VOCs, etc.)
The handbooks often contain incomplete information. Not all variables are well described.		
Mentor min/max QC are not generally useful.		

When problems are found, sometimes there is a need to reprocess the data. ARM has an active reprocessing team that is able to address all new reprocessing requests on a monthly basis, dependent on complexity. This workflow requires mentor engagement to review reprocessed data before it is either reprocessed again or disseminated to the community. If a user has downloaded data in the last five years, they are notified that these data have been reprocessed.

3.3.2 Challenges and Opportunities

The following discussion will follow an outline of discussing a challenge (labeled by number and a C) followed by opportunities (labeled by an O) that were discussed for that challenge. For all these challenges and opportunities, it is important to note that ARM has limited resources, and to address some of these challenges ARM will need to either use existing resources or reallocate resources from other areas.

1C: A limiting factor in many of the discussions around improving data quality, providing more reports/information to the user community, more user engagement, and many other items relates to the amount of time instrument mentors have available for these activities. Mentors have limited time and resources and have to prioritize activities. Most of the time, mentors prioritize ongoing operations to ensure continued operations and production of data.

1O: ARM has recently (2023) hired data analysts who are available as a resource with the goal of improving ARM's data for the users, whether through the creation of new data products or software, the analysis of data, or collaborations on projects with other ARM staff. There is a process, defined during the 2023 ARM Mentor Meeting, in which the mentors can request effort from these data analysts to further advance their systems. This could be through data analysis and advancing the data science aspects to improving ARM products.

As mentors continue to respond to user questions, frequently asked questions (FAQs) can be documented in the ARM instrument handbooks. If there is a need for further education on base "ARM 101" topics such as working with embedded QC (bit-packed QC), ARM can look at developing materials for new and existing users. Specifically for new users, there may be additional opportunities to provide Readmes and links to beneficial resources.

2C: ARM produces a lot of information that may not be effectively communicated or consumed by the user community. A part of this includes the variety of reports that are internal to ARM and have not been published for user consumption. As with 1C, additional effort is required in taking an internal report and publishing it as a technical report and even more to publish in a journal. There is a need to 1.) more effectively communicate this information to the users and 2.) determine what to devote effort to that is of interest to the community.

2O: The AMSG can play a role in 1.) determining which information is important to communicate and 2.) what mechanism will reach the greatest users. This could be routine communications from the AMSG or jointly with the ASR aerosol working group.

3C: Information on data quality is spread out across multiple areas. This includes 1.) embedded QC or QC variables in the files, 2.) DQRs, 3.) instrument handbooks, and 4.) technical reports detailing problems (UHSAS artifacts, Tracking Aerosol Convection Interaction Experiment [TRACER]/Eastern Pacific Cloud Aerosol Precipitation Experiment [EPCAPE] CCN closure). The variety of different locations to get this information makes it very easy for users to miss critical information.

3O: ARM can take small steps (and in some cases already is) to help improve this area but there is not a single item that is going to greatly improve it.

1. Automatically add DQR information to embedded QC variables on delivery.

2. Default to provide clean data sets. Automatically default to remove data impacted by a suspect or incorrect DQR or corresponding embedded QC flags. Puts the onus on the user to indicate that they want to work with data labeled as suspect.

3. While not discussed at the AMSG workshop, providing tools to "digitize" some of the information currently housed in handbooks and technical reports so that users can then apply it to their data sets.

4C: ARM has a lot of data products across various levels (defined by ARM) that are often hard for users to navigate. ARM has implemented rankings of measurement sources in Data Discovery, which is also not clear to users. Details of what processing, quality control, and retrievals that are in each data product as a map for each measurement type would provide a significant resource to the community.

4O: ARM mentors and staff have planned to develop a publication to document the processing performed at a and b-levels but it depends on resources. As ARM users continue to cite Data Object Identifiers (DOI), that information, along with download statistics, can be mined to steer users to products that users have downloaded either in conjunction with or instead of the products they are looking at along with data products used in papers in conjunction with the data they are looking at.

Additionally, there is value in providing composite data products that pull together information valuable for certain purposes such as closure analysis, new particle formation, or a general merged product that includes all the AOS variables.

5C: Documentation, specifically instrument handbooks, are inconsistent across instruments. Some instrument handbooks are using formats from the early 2000s and a number have not been updated recently.

5O: ARM has implemented a new handbook template and is working to ensure that all handbooks that have not been updated in the past three years are by the end of 2024. Significant changes or handbooks using a template older than the most recent two versions will be required to update to the new template. Mentors will be expected to update the handbook yearly going forward.

6C: ARM has been working on how to define and communicate uncertainty information to data users. Even with previous efforts, there is not a defined and consistent path forward for the communication of this information.

6O: As a first step, ARM should update previous reports on uncertainty (Sisterson 2017) and communicate that resource to users. ARM should prioritize ongoing efforts to standardize how uncertainty information is conveyed in data products through coordination with the Community Foundation (CF) standards community and then work to incorporate uncertainty information into ARM data files.

7C: DQ tools provide a great resource to the community in data exploration and analysis, but based on the survey to AMSG attendees, half of them are not aware of this capability. These capabilities were presented at the ARM/ASR PI meeting plenary session, which lends to previous discussions on effectiveness of communication but also to the science community consumption of this information.

7O: There is a lot of information on the DQ Office website (dq.arm.gov) but it is separate from the main ARM packages. Information may be lost in not including the DQ information more fully in the ARM pages. ARM should review and assess the need to further communicate DQ information on the main ARM pages.

8C: PIs provide a lot of valuable data to ARM that is available through the PI data area, which is linked outside of Data Discovery. The organization of this area is not conducive to user navigation due to the non-standard nature of PI products.

8O: The ADC is allocating effort towards bringing the IOP data into Data Discovery for easier dissemination. Additional resources are available through open-source software such as the Atmospheric data Community Toolkit (ACT; Theisen et al. 2024) to help PIs produce data sets following ARM standards.

9C: ARM data would see expanded usage through data sharing with and contributions to other organizational data centers. A barrier in easily sharing the data is the need to reformat ARM data to the different organization's requirements and the continued maintenance of that data processing and data contributions. Many of these organizations have different requirements and data submission avenues that compound the complexity of data sharing.

9O: ARM has the capability to develop VAPs in other formats. This depends on priorities of the VAP team and could take time to develop. Contributions from the community to open-source repositories that convert ARM data to different formats can streamline these efforts and provide new avenues for data sharing beyond the existing metadata and VAP avenues. It can also provide resources for other programs to follow suit with limited investment.

10C: ARM has a lot of tools in its repertoire; PIs have expressed a need for ARM to provide more productive ways to engage with ARM and the data. DQ Tools could fill a void here but are underused and unknown by a significant portion of the community.

10O: As to 7O, ARM can better highlight these tools for user community use. The field campaign dashboard can provide an interface for users to consume ARM reports and visualizations. This has been developed for major AMFs and ARM field campaigns and should be advertised more for the user community. ARM is also testing a customizable visualization dashboard that users (science and infrastructure) could tailor to their needs for near-real-time data monitoring and visualization.

3.3.3 Concluding Remarks

This ARM session highlighted critical areas for improving the accessibility, usability, and communication of data quality information. Key challenges include fragmented data quality reporting, inconsistent documentation, and limited mentor resources for user support. ARM has already taken steps to address these issues by hiring data analysts, developing new tools for data tracking and visualization, and standardizing instrument handbooks. However, further efforts are needed to streamline data quality information, make clean data sets more readily available, and enhance communication with the user community.

Engagement with the aerosol community remains essential to ensure diverse feedback is incorporated into ARM's ongoing improvements. By improving documentation, centralizing DQRs, and expanding the use of tools like the DQ Office website and visualization dashboards, ARM aims to provide researchers with clearer, more reliable data. The continued development of value-added products and efforts to expand data sharing across organizations will further enhance ARM's contributions to atmospheric research.

Ultimately, these efforts are geared toward making ARM data more user friendly, increasing confidence in the data, and fostering a stronger connection between ARM and the research community.

3.4 New Aerosol Measurement Techniques

Organizers: Jim Smith, Markus Petters

3.4.1 Overview

The purpose of this breakout was to identify up-and-coming aerosol instrumentation and analysis techniques that may be deployed by ARM. It is important for ARM and the broader community to be aware of the latest technologies that have recently become available or will be in the near future so that they can take advantage of them when the opportunity arises. Through presentations and discussion, the goal of this session was to identify the existence and state of emerging and maturing measurement and analysis technologies that cover the broad range of platforms that ARM uses and to gauge community interest in these new capabilities. In planning for the future of aerosol instrumentation in ARM, we will continue to serve the needs of the scientific community for years to come.

Presenters during this session highlighted two areas that are undergoing rapid development but have historically not been implemented at ARM sites to a great extent. The first is offline analysis of aerosol particle physical, chemical, and climate-related properties, which has benefited greatly from advances in laboratory instrumentation, such as ultra-high-resolution mass spectrometers, chemically resolved imaging, and measurements of IN and CCN activity on individual particles. The second area is the application of machine learning models for rapidly identifying aerosol source profiles and providing automated QA/QC of data sets. Since improvements to existing instrumentation is discussed in the Core Aerosol Measurements Breakout (Section 4.1), we instead devoted the remainder of the discussion to recent advances in instrument and instrument-development platforms, and what instruments are needed for these new platforms.

Three platforms were discussed: uncrewed aerial systems (UAS), commercial ships, and spatially distributed measurement nodes. The UAS discussion focused on the AAF's ArcticShark. While other UAS platforms exist, and tethered balloon systems also provide crucial information on vertically resolved aerosol properties, the ArcticShark is a unique resource that offers tremendous opportunities for research-grade instrumentation. The discussion of commercial ships as potential platforms for ARM instruments was motivated by a recent workshop convened by DOE in response to a new multi-agency program: Science Research on Commercial Ships (Science RoCS). The discussion on spatially distributed measurement nodes focused on new platforms under development by ARM, the mini- and micro-AOS, and how best to use these new platforms to get the most scientific benefits. A fourth “platform” was discussed during the session – the platform that ARM uses to develop new instruments called the SBIR program. Participants felt that the SBIR has led to exciting new capabilities within ARM, but some issues that need to be addressed to achieve the greatest benefits from the program.

3.4.2 Capabilities

With a payload of 100 lbs. and payload power of 2,500 W, the ArcticShark provides a platform for a current suite of measurements of atmospheric thermodynamics, physical, optical and chemical properties of aerosol particles, trace gases, land surface reflectance and temperature, and cloud droplet size distribution. Aerosol instruments are provided in switchable packages that address specific scientific goals, such as determining aerosol physico-chemical properties and size distributions. A modified water-based condensation particle counter has been deployed that allows counting and collecting particles aloft, with the latter used for offline analysis of particle composition by a new method called micro-nebulization aerosol mass spectrometry. In contrast to the UAS, the current consensus on the use of commercial ships as observational platforms from the workshop entitled “Observing Marine Aerosols and Clouds from Ships” is that basic aerosol instrumentation is not ready for autonomous operation. Instruments such as Doppler lidar, scanning mobility particle sizers, and filter samplers appear to be incompatible with the operating conditions on ships and must undergo further development if we wish to make this option viable. Aerosol instrument node development has been highlighted in ARM’s 2024 Aerosol Operations Plan, and this has led to the development of mini- and micro-AOS enclosures. Neither system has been fully specified, but it is anticipated that two mini-AOS will be deployed at the Bankhead National Forest (BNF) site in Alabama. The systems will run autonomously and will initially target aerosol size distribution and number concentration.

The SBIR and related STTR programs use small businesses to reach technological advances. Topics are decided by DOE and there is commonly a multi-year process between the first award and a deployable instrument. ARM offers infrastructure and data for SBIRs to validate and develop technologies. It was noted that some, but not all, SBIR awardees attend ASR/ARM PI meetings, and several opportunities exist for better leveraging this important resource.

The objective in offline aerosol analytics is to bring “the field into lab.” Using specially designed aerosol particle samplers, researchers can take advantage of a myriad of advanced research instruments to analyze individual particles. This approach places the resource-intensive instruments in the laboratory, relying on collection systems that are relatively inexpensive and more easily adapted to remote or harsh environments. DOE-funded labs such as the Environmental Molecular Sciences Laboratory (EMSL) provide many of these state-of-the-art laboratory resources that are undergoing rapid development. Another analysis area that has undergone rapid development is the application of machine learning to the analysis of complex data sets. DOE-funded research has led to the development of a trained machine learning (ML) model to rapidly identify source profiles using data from the ACSM. Since this approach uses site-specific information to train the model, it is most useful when source profiles change rapidly during continuous measurements at that site.

3.4.3 Opportunities

Recent UAS deployments have shown that newly developed platforms such as the ArcticShark can be quite successful at addressing important scientific questions related to vertically resolved aerosol properties. Nonetheless, current packages have focused on bulk and size-resolved particle sampling as well as particle number-size distributions. Future opportunities to add to these capabilities with measurements and samplers that address VOC concentrations, gas and particle fluxes, and climatically relevant aerosol properties should be considered. The recent attention paid to shipborne measurements can be leveraged by aligning the instrument goals with those required for autonomous, spatially distributed measurements on land. Exciting new developments in lower cost CPCs and SMPS systems can create opportunities for instrumenting mini- and micro-AOS platforms. More generally, there has been significant investment in “low-cost sensor” systems that, while designed for air quality measurements, may be relevant for some ARM objectives. In general, the consensus was that if distributed aerosol nodes and shipborne platforms are a continuing vision for ARM, then efforts should be made to pool resources for a unified design that can be used on ship and land, leveraging work on common issues such as unattended operation and inlet design. While nodes are initially targeting aerosol size distribution and number concentration, there is the opportunity to expand these measurements to include optical properties, CCN, INP, trace gases, and potentially more according to the specific scientific needs and available instrumentation.

Recent success in “bringing the field into the lab” through sample collection combined with offline laboratory analysis shows the importance of considering that equally with bringing lab instruments into the field. ARM should consider offline analysis approaches whenever it is not possible to bring instruments into the field. One example is the frequent need for VOC measurements during IOPs. If real-time measurements such as PTR-MS are not available, then offline approaches that include canister or sorbent tube sampling should be considered. Machine learning approaches that supplement QA/QC analysis of data sets should be expanded to address the need for accurate data analysis that is not so labor intensive.

For the SBIR and STTR programs, ARM will continue its support by funding projects and providing critical infrastructure and data for use in developing and validating technologies. Opportunities to encourage participation of this community at the ARM/ASR PI meeting should be considered, such as a recent breakout session on new instruments. ARM should also consider designating individuals to reach out and engage Phase 1 or 2 PIs.

3.4.4 Roadblocks

Challenges associated with creating automated, low-power instruments for uncrewed arial vehicles, distributed aerosol measurement nodes, and shipborne instruments are numerous. Uptime and reliability can be challenging for any new instrument that implements state-of-the-art technologies. All the demands of AOS instruments, such as inlet designs and sample stream relative humidity (RH) conditioning, apply to the development of mini- and micro-AOS systems. Numerous roadblocks were identified at the workshop on commercial shipborne measurements, including logistical challenges that include the use of hazardous materials as well as instrument-related challenges such as eye safety of lidars. Most are solvable, but hard, problems that require instrument development, and a recent SBIR call has focused on these challenges. The SBIR program has led to exciting new instruments, but there are roadblocks that

impact their efficacy in supplying suitable instruments in a timely manner. Regarding the former, not all instruments that benefit ARM science fit the SBIR/STTR model for commercial viability. Regarding the latter, the
~five-year timeline for instrument development via this program presents challenges for addressing current ARM needs.

3.4.5 Concluding Remarks

Over the past several years, ARM’s significant investment in the UAS program has resulted in excellent science that will only get better as PI-led projects increase in number. New instrument capabilities for this platform should be considered, such as measurements and sampling of VOCs, fluxes, and climate-relevant aerosol properties. Opportunities have opened for exploring the use of commercial ships as platforms for instruments that require minimal user intervention. Technology developed in ARM can have trickle-down effects through the development of robust instruments, such as the development of an SMPS that can run autonomously in the Amazon rainforest. ARM is investing in the development of aerosol “nodes” (mini- and micro-AOS), initially for the BNF site but potentially for other AMF deployments. Initially targeting aerosol size distribution and number concentration, these should be expanded to include optical properties, CCN, INP, trace gases, and potentially more. The development of these flexible packages has potential applications in a variety of projects such as those that survey the suitability of a site for future measurements, or as a pre-deployment instrument package that could inform the placement of a larger instrument suite. This effort and the RoCS program are complementary and should be developed accordingly. The SBIR program has led to exciting new instruments, but there are challenges. Do all instruments that benefit ARM science fit the SBIR model for commercial viability? Do the timelines work well? Despite these questions, ARM should consider activities that support more active participation of awardees in ASR/ARM science. Lab analysis capabilities for particle samples are impressive and promise to continue to be so, from ultra-high-resolution mass spectrometers, to chemically resolved imaging, to measurements of IN and CCN activity. We should be thinking about “bringing the field into the lab” as much as we are thinking about “lab to field.” Finally, recent success in applying a machine learning model to rapidly identify aerosol source profiles from ACSM measurements highlights the need to expand this work into other areas, such as spectral absorption and size distribution.

3.5 Measurement Uncertainties

Organizers: Olga Mayol-Bracero, Richard Moore

3.5.1 Overview

Breakout session presentations discussed substantial recent progress on operational activities to develop particle standards following Smith and Riemer (https://tinyurl.com/particlestandards) as well as inter-instrument comparisons addressing dry aerosol microphysical parameters (number, volume, and size-resolved concentrations), dry mass-volume comparisons, and exploring the consistency of aerosol hygroscopicity and humidifications. Other presentations discussed the role of distributed networks of low-cost sensors and how a large number of mini-AOS instrument suites would have the advantage of capturing spatial heterogeneity but with the cost of increased instrument uncertainty. If we opt for low-cost sensors, then the key is to have a large number of them. Finally, we discussed how models do (or do not) consider measurement uncertainties.

3.5.2 Challenges and Opportunities

A challenge is to quantify measurement uncertainties instead of merely reporting observational variability; although, both metrics have scientific value. Sisterson (2017) reports a large collection of measurement uncertainties for various ARM instruments, and there is an opportunity to expand upon and refine that work to include references and provenances for the reported values as well as to better incorporate the instrument uncertainties directly into the ARM data files. At a minimum, a relative uncertainty (%) and offset or lower limit of detection (LLOD) should be reported. McComiskey et al. (2021) noted the need for a centralized calibration facility, and progress was reported with regard to the CAMS (https://www.bnl.gov/envsci/cams/) main laboratory at Brookhaven National Laboratory toward addressing the goal of becoming a nationwide aerosol calibration and measurement science center that will provide traceable measurement services to ARM and beyond. The CAMS facility will enable a robust assessment of instrument variability across sites and over time, and there is an opportunity to better integrate these efforts with the European CARGO-ACT research infrastructure (http://www.cargo-act.eu/). Yet, there is also recognition that field-deployable transfer standards and calibration procedures are needed to complement the centralized effort due to the potential for inadvertent instrument configuration changes or damage that may be incurred during shipping.

3.5.2.1 Short-Term Action Items

- Update uncertainties in Sisterson (2017), add references, and harmonize with data file metadata
- Continue and expand automated diagnostic closure efforts
  - hygroscopicity closure (CCN, SMPS, ACSM): publish, share code
  - microphysics: continue development
  - optical properties: future work
- Assess the consistency between inlets and measurements (coarse aerosol, T/P/%RH)
- Consider the role of low-cost sensors for capturing spatial heterogeneity and determine what level of uncertainty is acceptable relative to state-of-the-art techniques.

3.5.2.2 Longer-Term Action Items

1. Progress CAMS and the development of field-deployable transfer standards and coordinate these activities with international efforts to standardize calibration and operation procedures (e.g., CARGO-ACT).
2. Continue discussions and outreach regarding how to best communicate uncertainties (e.g., file headers, separate variables, documents).
3. Develop, mature, and deploy ambient aerosol measurements alongside dry measurements to aid in efforts to reconcile in situ and remote-sensing measurements and to better quantify the role of aerosol water in changing particle size and optical properties.

3.5.3 Concluding Remarks

The session highlighted progress in developing particle standards, comparing aerosol measurement techniques, and evaluating the trade-offs between high-precision and low-cost sensor networks for capturing spatial variability. A key challenge identified is the need to quantify and report measurement uncertainties more rigorously, supported by efforts such as expanding uncertainty documentation (Sisterson 2017) and advancing centralized calibration through CAMS. Short-term priorities include updating uncertainty data, improving diagnostic closure studies, and assessing sensor performance, while longer-term goals focus on standardizing calibration practices internationally and enhancing integration of ambient and dry aerosol measurements.

3.6 Roadmap to Modeling

Organizers: Jerome Fast, Nicole Riemer

3.6.1 Overview

Earth system models, high-resolution models, and observations are key tools for improving our understanding of the natural and human-influenced atmospheric processes affecting Earth's climate. Despite recent scientific advances, models still contain biases arising from knowledge gaps and imperfect parameterizations of important physical and chemical atmospheric processes. The impacts of these biases are multifaceted, but they make important contributions to uncertainties in the net change of the Earth system energy balance between pre-industrial and present-day periods. Much of this uncertainty has been attributed to short-lived climate forcers, such as aerosol-cloud interaction (ACI) processes. One of the many challenges in reducing ACI uncertainties is for models to better represent the aerosol processes and properties that are highly variable in space and time. Observations of aerosol number, size distribution, composition, mixing state, phase, optical properties, cloud-nucleating properties, and gas-phase precursors are needed to evaluate models and develop improved parameterizations. However, there are relatively few aerosol observations compared to meteorological, cloud, and radiation measurements. Global climate models usually use measurements from satellite or routine surface monitoring networks. Satellites obtain column-integrated quantities, and surface monitoring networks are available only in a few regions of the world. Both satellite and surface monitoring networks lack measurements of key aerosol properties. ARM does provide useful aerosol measurements, but there are roadblocks for modelers to take advantage of these measurements.

Three presentations were given by global and regional modelers to provide perspectives on how modelers use aerosol measurements and on roadblocks and strategies needed to better address modelers' needs.

The first presentation by Po-Lun Ma provided an overview of how ARM aerosol data is currently being used to evaluate DOE's Energy Exascale Earth System Model (E3SM). E3SM_diags is a tool that evaluates E3SM simulations with monthly averaged ARM observations. Most of the observations used by E3SM_diags are meteorological and radiation variables. While E3SM_diags includes CCN observations, it does not use other ARM aerosol observations. Therefore, the Earth System Model Aerosol-Cloud diagnostic (ESMAC_diag) tool has been developed recently to exploit a larger range of ARM aerosol measurements (number, composition, size distribution) from four geographical regions (Eastern North Atlantic, central United States, northeastern Pacific, and Southern Ocean) to evaluate the simulated aerosol life cycle and ACI processes (Tang et al. 2022, 2023). A combination of long-term and field campaign ARM measurements is used, depending on the region. Both state and process-oriented diagnostics are computed. The process-oriented diagnostics focus on ACI, such as relationships between cloud droplet number (Nd), liquid water path (LWP), and CCN. For example, ESMAC diagnostic showed that simulated aerosol mass from E3SM version 2 was too high over the Eastern North Atlantic, which may be due partly to wet scavenging being too low. While not perfect, a high-resolution regionally refined version of E3SM was found to better represent ACI processes over the Eastern North Atlantic since the correlation of LWP and Nd improved compared to the traditional coarse spatial resolution version of E3SM. In addition to shedding light on model uncertainties, the diagnostics can be used to reconcile differences between common satellite and ARM measurements. The presentation also pointed out weaknesses in E3SM aerosol treatments where new ARM observations would be useful (e.g., SO_2, sulfuric acid).

The second presentation by Johannes Mülmenstädt described a recent NASA workshop on designing observations for climate applications and reported the overall conclusions. While the workshop did not focus on aerosols per se, strategies were discussed on how satellite observations should be best configured or selected to constrain climate models. Many of those conclusions based on satellite observations could be applied to in situ and local remote-sensing measurements that ARM conducts. One conclusion was that a systematic approach is needed to identify which observations will best improve climate model predictions. Since cloud state and cloud feedbacks are fundamentally controlled by different model parameters, constraining cloud state is likely not enough to improve cloud feedbacks. While both cloud and aerosol parameters contribute to clear-sky and cloudy radiative fluxes, previous studies have noted that those parameters have different effects under pre-industrial (lower CO_2 and aerosol) and present-day conditions (higher CO_2 and aerosol). Therefore, better understanding the pre-industrial and perturbed climate may require a different set of observations. The workshop proposed that the global modeling community could provide essential input into the design of observations (where, when, what) using a framework known as observing system simulation experiments (OSSEs). While it may be useful to include OSSEs in ARM proposals to justify what type of measurements are needed, conducting OSSEs are nontrivial exercises that are not feasible during a typical ARM proposal timeframe of a few months. This suggests a need for the global modeling, process modeling, and observations community to come together and provide a capability that prioritizes new measurements.

The third presentation by Jerome Fast described the use of a current operational regional chemical transport model (Dx = 12 km) to estimate the spatial variability of aerosols around the ARM BNF site, in anticipation of the upcoming measurements. Some variables had more spatial variability than others. SO_2 was found to have the largest spatial variability, while AOD had the lowest. The model demonstrated large spatial variations in aerosol properties around BNF, confirming that the planned distributed aerosol measurement sites will likely capture some of that variability; however, plumes from nearby cities and/or fires transported over the BNF region may not be sampled depending on the wind direction. The model output also includes aerosol and precursor trace gas species that are not currently measured by ARM. Regional modelers could use this information to help prioritize new ARM measurements to help improve aerosol predictions.

3.6.2 Challenges and Opportunities

A discussion session followed that can be divided into the following four subjects that described roadblocks, needs, and opportunities.

What types and form of data do modelers want? A recurring theme was that modelers often lack the time and bandwidth to engage directly with instrument mentors. To increase communication between observational and modeling scientists will require a change in culture, and changing the culture in the modeling community is largely beyond ARM's control. What ARM can do is reduce barriers by making data easier to find, interpret, and use. Participants emphasized that Data Discovery searches often return hundreds of results, making it difficult to determine which datastreams are most relevant for modeling studies. Several practical steps were suggested. One suggestion was to have a web page geared towards modelers, listing the most useful datastreams for modeling applications. The datastreams used by ESMAC_diag is a starting point that demonstrates which aerosol data has been useful for the E3SM community for model evaluation purposes. ARM may also want to host a web page that points users to existing diagnostic tools that access ARM data. Surveys could also be conducted where modelers could rank which aerosol data is necessary for modelers. Similar to the ARM Best Estimate VAP, including more aerosol variables into climatological data sets (i.e., monthly averaged) would be useful for climate modelers that may not need high-time-resolution (i.e., 1 s) data. Having data files in a consistent format was another need, including ways to quickly understand the data before using it. Knowing observational uncertainty is essential, but the details are often too instrument-specific to digest quickly. Providing concise, standardized uncertainty summaries would significantly lower the barrier to data use.

What do modelers need from observations? One suggestion was that a mechanism is needed that allows modelers to work together. ARM does have "translators" tasked with making ARM measurements accessible to the scientific community. Most of these translators are grouped by subject matter (i.e., clouds, aerosols), but there is one translator with "climate modeling" in the title. It is possible that the modeling community is not aware of ARM translators or how to take advantage of their expertise. Or perhaps all translators need to have connections to models in some way. Another suggestion was to have a meeting with ARM translators and modelers so that they can better understand each other's perspectives. ARM personnel are not aerosol modelers, so such an interaction will help translators understand the capabilities of regional and global models, how models represent aerosol processes, and what measurements would be useful to evaluate models. In addition, this interaction will inform aerosol modelers of measurements that they might not know exist.

What type of aerosol observations are modelers not getting? While ARM provides a wide range of measurements on aerosol microphysical and optical properties, modelers noted several gaps that limit process understanding and evaluation. Trace gas measurements are needed to understand the chemical gas-to-chemical partitioning processes, and modelers could prioritize which instrumentation and/or trace gases would be desired. This information could be obtained via a survey. While ARM uses the ACSM instrument to characterize aerosol composition, additional measurements of aerosol composition (i.e., more sites) and speciation is desired. In the past, filter sampling was used for aerosol composition, but this technique is expensive. Modelers suggested that ARM revisit this concept, since some data with more composition speciation at a lower time resolution would be better than no information at all. One comment was that modelers tend to gravitate towards gridded data, such as global reanalysis products, because of the greater spatial coverage. ARM observations are usually point measurements or a series of point measurements in a region and modelers have struggled how to interpret the representativeness of such measurements.

Some of the modelers described measurements and capabilities that would be useful, but that ARM does not currently provide. One example is a balloon platform that has both cloud and aerosol instrumentation that can provide vertical profiles within and outside of clouds. This information is very important to better understand aerosol-cloud interactions. The current tethered balloon system (TBS) and UAS are not currently suited to this task. More measurements of CCN as a function of supersaturation and droplet number concentration (either in situ or improved retrievals) are desired. Measurements at a site located near the interface of pristine and polluted conditions is desired to understand the aerosol life cycle and aerosol-cloud interactions. The Eastern North Atlantic (ENA) site is one such location, but other similar sites would be useful. These are just examples, and a larger workshop with more participants would be needed to create a comprehensive list of measurement needs from the aerosol modeling community.

Focus on what ARM does well, such as understanding different atmospheric processes. Participants emphasized that ARM's unique strength lies in its co-located, multi-year, multi-variable measurements of aerosols, clouds, radiation, and meteorology—capabilities unmatched by most global networks. A wide range of aerosol measurements from satellite and ground-based sampling networks are used by the global modeling community. The advantage of satellite measurements is their global coverage of column-integrated aerosol optical properties. This information is very useful, but satellite retrievals cannot quantify aerosol microphysical properties that control aerosol optical and cloud-nucleating properties. Most of the ground-based sampling networks collect a limited number of aerosol state values. Some networks, such as AERONET, have worldwide coverage, but AERONET only provides AOD data. Most networks, however, are in densely populated regions such as North America, Europe, and East Asia. The IMPROVE network is one such example that provides time-averaged aerosol composition data, which is one component of aerosol microphysical information. Therefore, modelers need to piece together these disparate data sets from multiple networks and search for other coincident meteorological measurements. In contrast, ARM is a unique facility that collects a wide range of coincident aerosol and meteorological measurements, with the number of atmospheric variables at the ground and aloft far exceeding any other measurement network. While there are few long-term fixed sampling sites, ARM provides such coincident data for many regions throughout the world via short-term (~1 year) field deployments. The challenge appears to be less about capability and more about visibility and communication. Having a small number of users demonstrate this utility may be the best means of demonstrating to the regional and global modeling community the value of ARM aerosol measurements.

3.6.3 Concluding Remarks

Earth system and high-resolution models, together with observations, are essential for understanding atmospheric processes that influence climate, yet significant uncertainties remain—especially regarding ACI. The workshop highlighted how emerging diagnostic tools, such as ESMAC_diag, are beginning to broaden the use of ARM aerosol measurements to evaluate and improve model performance. Participants also emphasized that better-designed observations, clearer pathways for accessing data, and improved coordination between observational and modeling communities are needed to accelerate progress. Key challenges include gaps in trace-gas and vertical-profile measurements, limited aerosol composition and CCN information, and persistent barriers that make it difficult for modelers to identify and interpret relevant datastreams or engage with instrument mentors.

At the same time, there are clear opportunities: strengthening communication between modelers and ARM scientists, refining data discovery tools and formats, expanding measurement types and locations, and leveraging ARM's unique capability to provide comprehensive, coincident aerosol and meteorological observations for model evaluation and development. Together, these steps would enable more effective use of ARM data in regional and global models and help reduce longstanding uncertainties in aerosol processes and aerosol-cloud interactions.

3.7 Large Spatial and Temporal Science Studies

Organizers: Chongai Kuang, Damao Zhang

3.7.1 Overview

Aerosol process studies often depend critically on spatially and temporally extensive measurements. Aerosols can exhibit high spatial and temporal variability due to their disparate sources, short atmospheric lifetimes, and strong coupling to the surface and surface-type (e.g., land versus ocean). Surface controls on aerosol sources (e.g., vegetative-driven emissions of VOCs, urban-driven emissions of SO_2), sinks (e.g., dry deposition) can vary significantly over short distances, leading to complex interactions between aerosol evolution and land-surface heterogeneity. Aerosol advection adds additional complexity to surface controls due to simultaneous emission, mixing, and processing during transport. Aerosol processes can also exhibit strong temporal variability across scales spanning the diurnal, seasonal, and inter-seasonal cycles. Many aerosol processes (e.g., new particle formation) also exhibit strong diurnal-to-seasonal (and even inter-seasonal) variability due to their strong (and often complex) dependence on (and between) photo-chemistry, environmental thermodynamics, atmospheric kinematics, and long-term trends in emissions variability and land-use change.

ARM observatories can address (and have addressed) these large (and often multi-scale) spatiotemporal observational needs by providing long-term (e.g., seasonal to inter-seasonal), continuous, comprehensive measurements over regions that can be quite spatially extensive (e.g., 10s-100s kms). This breakout session topic was organized to identify existing capabilities, new opportunities, and challenges to continue to advance impactful, large-scale science. This breakout session invited participants to discuss and identify:

- Creative deployment, modeling, and data-product development strategies to (better) integrate ARM measurements over larger spatial (e.g., 100s kms) and temporal (e.g., decadal) scales;
- Collaborations (and how to build/sustain them) with other regional-to-national measurement networks (e.g., IMPROVE, ASCENT, NEON, AmeriFlux); and
- A prioritized set of compact, (near) autonomous atmospheric and aerosol instruments that can be deployed in a spatially distributed network around an observatory.

Session presenters provided overviews on topics including: analysis of aerosol seasonal variability; the integrated analysis of surface aerosol, column atmosphere, and cloud properties; multi-scale spatiotemporal modeling of organic aerosol; aerosol vertical profile data products; and aerial science enabled by uncrewed aerial systems.

3.7.2 Capabilities and Opportunities

1. **Spatially distributed measurements:** Deploying a subset of ARM instruments around central observatories can improve the assessment of site representativeness, and will help in distinguishing local from background aerosol, as well as understanding advective contributions. To support this effort, ARM is investing in the development of two “mini-AOS” units (e.g., miniaturized scanning electrical mobility sizer + optical particle counter (mSEMS+OPC): 10 nm-25 microns) for deployment at ARM-BNF supplemental sites, along with “micro-AOS” units (e.g., portable optical particle spectrometer [POPS]: 180 nm-3 microns) deployed at as part of the Coast-Urban-Rural Atmospheric Gradient Experiment (CoURAGE) field campaign.
2. **Aerial platforms:** The use of AAF, such as UAS, can help address spatial measurement gaps. ARM’s ArcticShark UAS can provide in situ aerosol measurements over a maximum distance of approximately 26 miles from the airfield, flying between ~500 feet above ground level (AGL) and 15,400 feet above mean sea level (MSL). This capability enables ArcticShark to cover large areas and generate aerosol vertical profiles using a parking-garage flight pattern. Additionally, the UAS can operate both below and above clouds, providing critical data to improve our understanding of aerosol-cloud interactions. ARM’s new research aircraft, the Bombardier Challenger 850 Regional Jet, is expected to support proposal-driven campaigns in FY27, offering in situ measurements over even larger regions.
3. **Aerosol vertical profiling with active remote-sensing measurements:** ARM is making progress on aerosol profiling by releasing the newly developed Aerosol Feature Mask (LIDARAEROMASK) VAP. The VAP uses lidar backscatter profiles to identify aerosol features with a vertical resolution of 30 meters and a temporal resolution of 30 seconds. Recently, ARM deployed a HSRL at the SGP site. In conjunction with the Raman lidar (RL), these multi-wavelength lidar measurements enable the retrieval of vertically resolved aerosol microphysical properties using the well-established “3β+2α” method. The ARM HSRL provides aerosol extinction coefficients (α) at 532 nm and backscatter coefficients (β) at both 532 and 1064 nm, while the ARM RL provides aerosol α and β at 355 nm. ARM is actively collaborating with NASA's Langley Research Center (LaRC) to implement their algorithms on ARM HSRL and RL data, leading to the development of the new AEROPROF VAP. This VAP will be extended to the ARM BNF site, where both ARM HSRL and RL will be deployed.

3.7.3 Roadblocks/Needs

Modeling: While more spatially extensive measurements (10s to 100s km) over longer-duration periods (3-5 years) can help address the controls of large-scale spatial heterogeneity (e.g., in precursor emission, meteorology) and inter-annual variability (e.g., in soil moisture, convective activity) on aerosol processes, there continues to be a critical need for modeling to help fill in the gaps in observation and to integrate observations across multiple scales and measurement platforms (e.g., surface in situ, remote-sensing, tower-based, and extended sites). Additionally, there was some discussion on pre-deployment modeling activities (perhaps during the proposal development phase using ARM High-Performance Computing [HPC]) “modeling” for the purposes of site selection/design, measurement/sampling design, all pointed towards uncertainty reduction/process understanding.

IOPs: There was a desire to provide operational support (e.g., technicians, inlets, data collection) for guest PI deployment at supplemental sites (e.g., at CoURAGE [CRG] and BNF) which would provide detailed microphysical observations more typically seen at main sites. A “schedule” of IOPs targeting certain seasons (e.g., winter/summer contrast, vegetative growing season, convective season) would help PIs to organize their own deployments to increase science impact across the coupled surface-aerosol-convection continuum.

Regime classification: The topic of aerosol representativeness came up frequently, where it would be helpful to have tools and/or data sets that would provide information on the degree to which sampled aerosol was locally formed versus advected into the domain, and (related) the degree to which the atmospheric environment during aerosol sampling was more locally forced versus synoptically forced. There was some discussion on the use of frontal analysis from satellite data to identify days/regimes that were more quiescent (compared to synoptically forced), when one would expect stronger land-atmosphere coupling controls on the aerosol environment.

Distributed sampling: While there was general consensus that a measurement of the aerosol number-size distribution was a high priority for the mini-AOS, there were some questions regarding what the next high-priority aerosol measurement should be (e.g., optical properties, water-uptake, chemical composition). There was also some question about how to decide where to deploy these distributed sampling systems, and how modeling can be used to support site selection (as well as measurement priorities). While the mini-AOS is currently planned for deployment with supplemental sites for good reasons (e.g., existing power, data infrastructure, site operations support), future deployments may be at locations where such supporting infrastructure does not exist, and where ARM atmospheric profilers that normally accompany a supplemental site to provide atmospheric column context are not deployed. For those AMF deployments where the AOS is de-coupled from the main site, there was some concern about having enough measurements of atmospheric thermodynamics/kinematics with the AOS to provide context.

3.7.4 Concluding Remarks

Aerosol process studies require extensive spatial and temporal measurements due to aerosols’ high variability and dependence on surface type, sources, and atmospheric processes. ARM addresses these needs through long-term, comprehensive observations and is advancing capabilities for spatially distributed and vertically resolved measurements. Efforts include developing mini-AOS and micro-AOS units for networked, distributed deployments, expanding aerial measurements with UAS platforms like ArcticShark and a new research aircraft, and enhancing aerosol vertical profiling with new lidar-based products (e.g., LIDARAEROMASK, AEROPROF VAPs). Key needs include integrating modeling to bridge observational gaps and guide measurement deployment design, improving support for IOPs, developing tools for aerosol regime classification and representativeness, and refining strategies for distributed sampling and site selection to ensure meaningful, scalable observations across diverse atmospheric environments.

4.0 Recommendations

Here the workshop-derived recommendations are listed by AMSG Workshop Target Areas. Note that when a recommendation was discussed in one or more breakout sessions, the content was combined into a single actionable item, with copies placed under the relevant target areas.

1. Engage with strategic partners (Gannet Hallar/Tim Onasch)
   - Continue and expand partnerships with NOAA's FAN, ASCENT, and the pan-European ACTRIS, along with other regional-to-national measurement networks (e.g., IMPROVE, NEON, AmeriFlux) to use and enhance ARM sites. This can include guest instrumentation at the site, or incorporating ARM instruments into spatially broader networks.
   - Serve as a leader for the CARGO-ACT research infrastructures.
   - Continuing progress on CAMS and the development of aerosol field-deployable transfer standards, coordinated with international efforts to standardize calibration and operation procedures (e.g., CARGO-ACT).
   - Motivate outside partners to use ARM data via strategic data sharing via widely used data portals. To accomplish these extensive partnerships, we recommend a new hire responsible for outreach/coordination with other international scientific networks.
   - Continue to partner with national and international networks to use and enhance ARM sites. This can include guest instrumentation at the site, or incorporating ARM instruments into spatially broader networks.
   - Continue to use and support the SBIR and related STTR programs to develop new instruments and measurement techniques for use within ARM's network and the broader scientific and monitoring communities. Encourage SBIR/STTR PIs to attend ARM/ASR PI meetings and to directly interact with ARM personnel and ASR project PIs.
2. Large spatial and temporal science studies (Chongai Kuang).
   - Create a prioritized set of compact, (near) autonomous atmospheric and aerosol instruments that can be deployed in a spatially distributed network around an observatory.
   - Build creative deployment, modeling, and data-product development strategies to better integrate ARM measurements over larger spatial (e.g., 100s kms) and temporal (e.g., decadal) scales.
   - Continue and expand partnerships with NOAA's FAN, ASCENT, and the pan-European ACTRIS, along with other regional-to-national measurement networks (e.g., IMPROVE, NEON, AmeriFlux) to use and enhance ARM sites. This can include guest instrumentation at the site, or incorporating ARM instruments into spatially broader networks.
3. Roadmap to modeling (Jerome Fast/Nicole Riemer)
   - Minimize the barriers between instrument mentors and modelers. For example, making it easier to find aerosol observations and having more refined searches on Data Discovery are needed.
   - Up-and-coming aerosol instrumentation and analysis techniques that should be prioritized for deployed by ARM include offline analysis of aerosol particle physical, chemical, and climate-related properties, which has benefited greatly from advances in laboratory instrumentation, such as ultra-high-resolution mass spectrometers, chemically resolved imaging, and measurements of IN and CCN activity on individual particles.
   - UAS and TBS newly developed platforms are successfully characterizing vertical profiles, and require new instrument packages focusing on VOC concentrations, gas and particle fluxes, and climatically relevant aerosol properties.

4. Core Aerosol-Related Measurements (John Shilling/Lynn Russell)

- Focus on aerosol coarse-mode measurements, while carefully considering sampling losses, with a focus on INP measurements.
- Implementing two new measurements, one of black carbon and another of VOCs at all sites.
- ARM continues to explore and prioritize measurements of aerosol hygroscopicity (in sub- and supersaturated conditions), with a focus below d < 50 nm, to provide composition information.
- Move towards size-resolved measurements of INP, CCNC, and BC measurements.
- A new VAP that includes a retrieval of aerosol size distributions from ARM lidars.

5. New Aerosol Measurement Techniques (Jim Smith/Markus Petters)

- Up-and-coming aerosol instrumentation and analysis techniques that should be prioritized for deployed by ARM include offline analysis of aerosol particle physical, chemical, and climate-related properties, which has benefited greatly from advances in laboratory instrumentation, such as ultra-high-resolution mass spectrometers, chemically resolved imaging, and measurements of IN and CCN activity on individual particles.
- ARM should continue to focus on the application of machine learning models for rapidly identifying aerosol source profiles and providing automated QA/QC of data sets.
- UAS and TBS newly developed platforms are successfully characterizing vertical profiles, and require new instrument packages focusing on VOC concentrations, gas and particle fluxes, and climatically relevant aerosol properties.
- We suggest that ARM continues to invest in autonomous (e.g., marine) and spatially distributed measurements, including new lower cost CPCs and SMPS systems for mini- and micro-AOS platforms, and expand these nodes to include optical properties, CCN, INP, trace gases, and potentially more.
- Continue to use and support the SBIR and related STTR programs to develop new instruments and measurement techniques for use within ARM's network and the broader scientific and monitoring communities. Encourage SBIR/STTR PIs to attend ARM/ASR PI meetings and to directly interact with ARM personnel and ASR project PIs.

6. Measurement Uncertainties (Olga Mayol-Bracero/Rich Moore)

- Consider the role of low-cost sensors for capturing spatial heterogeneity and determine what level of uncertainty is acceptable relative to state-of-the-art techniques.
- Continuing progress on CAMS and the development of aerosol field-deployable transfer standards, coordinated with international efforts to standardize calibration and operation procedures (e.g., CARGO-ACT).
- Develop, mature, and deploy ambient aerosol measurements alongside dry measurements to aid in efforts to reconcile in situ and remote-sensing measurements and to better quantify the role of aerosol water in changing particle size and optical properties.
- ARM should continue to address key challenges including fragmented data quality reporting, inconsistent documentation, and limited mentor resources for user support. Continue discussions and

outreach regarding how to best communicate uncertainties within data sets (e.g., file headers, separate variables, documents).

7. Improving the Understanding and Accessibility of ARM Aerosol Data (Adam Thiesen/Alyssa Sockol)

- ARM should continue to address key challenges including fragmented data quality reporting, inconsistent documentation, and limited mentor resources for user support. Continue discussions and outreach regarding how to best communicate uncertainties within data sets (e.g., file headers, separate variables, documents).

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Appendix A

AMSG Organizational Structure

The AMSG reports to ARM Technical Director and is made up of experts from across ARM and the atmospheric science community.

ARM Technical Director: Jim Mather

Associate Director for Operations for the multi-lab DOE Atmospheric Radiation Measurement (ARM) User Facility: Nicki L. Hickmon – Argonne National Laboratory

AMSG members include:

- Gannet Hallar, AMSG Co-Chair
- Tim Onasch, AMSG Co-Chair
- Jerome Fast, Science Representative
- Chongai Kuang, Science Representative
- Olga Mayol-Bracero, Science Representative
- Rich Moore, Science Representative
- Markus Petters, Atmospheric System Research (ASR) Aerosol Processes Working Group Co-Chair
- Nicole Riemer, ASR Aerosol Processes Working Group Co-Chair
- Lynn Russell, Science Representative
- John Schilling, ARM Aerosol Data Translator
- Jim Smith, Science Representative
- Alyssa Sockol, ARM Data Quality Office
- Adam Theisen, ARM Instrument Operations Manager
- Damao Zhang, ARM Instrument Mentor

Appendix B

AMSG Strategic Planning Workshop Agenda

The 2024 AMSG Strategic Planning Workshop was hosted by Prof. Gannet Hallar at the University of Utah in Salt Lake City. Below is the final agenda of the workshop.

[Department of Atmospheric Sciences - The University of Utah]

Agenda

2024 AMSG strategic Planning Workshop

July 9-10, 2024

Salt Lake City, Utah

All times Local (Mountain Time)

<u>July 8, 2024</u>

1800 – 2000 Welcome Gathering (no host) Optional gathering for meet-and-greet

Franklin Ave Cocktails and Kitchen

<u>July 9, 2024</u>

Cleone Peterson Eccles Alumni House - Dumke Reception Room

155 Central Campus Drive, Salt Lake City 84112

0900 – 1000 Introduction and Goals of the Workshop (five-year strategic plan)

1000 – 1030 Paolo Laj, Head, Global Atmosphere Watch (GAW) Programme
Title: ***Benefits of Engagement with External Strategic Partnerships***

1030 – 1045 **Break**

Session Goals: Discuss strategic initiatives needed to advance ARM science under each topic.

1045 – 1215 **<u>Session 1</u>**

Option 1 – Core Aerosol-Related Measurements – Leaders: John Shilling, Lynn Russell

Option 2 – Engage with strategic partners – Leaders: Gannet Hallar, Tim Onasch

Option 3 – Improving the Understanding and Accessibility of ARM Aerosol Data – Leaders: Adam Thiesen, Alyssa Sockol

12:15 – 1315 **Lunch**

1315 – 1445 **<u>Session 2</u>**

Option 1 – New Aerosol Measurement Techniques – Leaders: Jim Smith, Markus Petters

Option 2 – Measurement Uncertainties – Leaders: Olga Mayol-Bracero, Rich Moore

1445 – 1500 **Break**

1500 – 1630 **<u>Session 3</u>**

Option 1 – Roadmap to modeling – Introduction: Jerome Fast and Nicole Reimer (5 min)

Context presentation: Po-Lun Ma: "Opportunities for advancing aerosol predictability in Earth system models using ARM aerosol measurements" (10 min)

Context presentation: Johannes Muelmenstadt: “Report on NASA workshop on Designing Observations for Climate Applications” (10 min)

Context presentation: Jerome Fast “Using models for OSSEs to guide measurement strategies” (10 min)

Discussion (55 min), topic including, but not limited to:

- Global modeling aerosol measurement needs
- Better connections with AeroCom/AeroSat community
- Data availability, uncertainty, and metadata
- Observing System Simulation Experiments (OSSEs)
- Aerosols in LASSO

Option 2 – Large spatial and temporal science studies : – Leader: Chongai Kuang

This breakout session invites participants to discuss and identify:

- creative deployment, modeling, and data-product development strategies to (better) link comprehensive and high-temporal-resolution ARM measurements with spatial information (scales: horizontal ~ 100s km, vertical ~ 10s km) and over longer time periods (scales: seasonal to inter-annual)
- collaborations (and how to build/sustain them) with other regional-to-national surface/aerial measurement networks (e.g., IMPROVE, ASCENT, NEON/AOP, AmeriFlux, NASA) to both contextualize ARM observations (in space and time) as well as provide an important reference for those networks
- opportunities to develop subsets of instruments (e.g., atmospheric thermodynamic profilers, aerosol size spectrometers) and deploy around a main site, to provide greater information about main site representativeness (e.g., local versus background)
- collaborations with satellite programs for which the joint application of ARM’s comprehensive measurements at a single point with satellite-based spatial information would be of particular benefit to the ARM user community

Block 1: 15:00 - 15:55, “Setting the Table”

15:00 – 15:05 Introduction (Chongai Kuang & Damao Zhang)

15:05 – 15:15 ARM Large-Scale Science (Chongai Kuang)

15:15 – 15:25 UAS-enabled Aerosol Science (Fan Mei)

15:25 – 15:35 Surface-through-Vertical Aerosol Science (Maria Zawadowicz)

15:35 – 15:45 Multi-scale Temporal Aerosol Science (Jim Smith)

15:45 – 15:55 Aerosol Vertical Profile Data Products (Peng Wu, pending)

<u>Block 2: 15:55 - 16:30, "Discussion"</u>

See above bullets in session description

1635 – 1715 Summary of Topics and Issues

<u>July 10, 2024</u>

0800 – 0900	Plans for Day 2 (Lightning Talks from each leader – short and informal talks giving Action Steps – Outline goals needed for strategic plan)
0900 – 1030	**<u>Session 1:</u>** Improve Existing ARM Systems and Programs – Keynote from Betsy Andrews, CIRES Research Scientist , NOAA Global Monitoring Laboratory
1030 – 1045	**Break**
1045 – 1245	**Session 2:** New Frontiers of ARM – Keynote from Allison McComiskey, NSF NCAR Associate Director; Director, Earth Observing Laboratory
1245 – 1330	**Working Lunch** – Discuss plan for complete workshop report
1400 – 1600	Work on writing assignment – Summary/Questions/Issues

Task – Complete questionnaire in Google document before leaving SLC

<u>July 11, 2024</u>

0900 – 1200 Small group writing session – includes one leader from each breakout session (i.e., AMSG committee members)

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