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ARM Aerosol Measurement Science Group 2019 Strategic Planning Workshop Report

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ARM

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Executive Summary

This report summarizes the results of a U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility workshop held in November 2019 to advance a science-based strategy for ARM's aerosol measurement program. This was the second such workshop since the Aerosol Measurement Science Group (AMSG) was chartered in 2015 to enhance coordination of ARM observations of aerosols and atmospheric trace gases with the needs of ARM users.

The results presented here reflect the AMSG's focus in recent years 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. Sessions held during the workshop range from interfacing with models through aerosol sampling strategies to calibration protocols and data products.

The AMSG workshops have been designed to recommend actions that will enable ARM to evolve and continue to meet its mission. To that end, the AMSG will develop an actionable plan from the recommendations outlined here. Some are well defined and can reasonably be accomplished in the short term. Others are less definite or of a larger scope that calls for a longer-term implementation. Further discussion will be required to develop and prioritize actionable items related to such areas. Task teams comprising the appropriate expertise and perspective from the AMSG and other members of the community will be formed to achieve this outcome.

Some particular topics are recognized as high priority, so plans are underway to develop task teams and to hold follow-on discussions to address them. Four areas currently being considered for short, focused discussion are 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.

Acronyms and Abbreviations

4D	four-dimensional
AAAR	American Association for Aerosol Research
ACSM	aerosol chemical speciation monitor
ADC	ARM Data Center
AeroCom	Aerosol Comparisons between Observations and Models
AERONET	Aerosol Robotic Network
AMF	ARM Mobile Facility
AMSG	Aerosol Measurement Science Group
AOD	aerosol optical depth
AOS	Aerosol Observing System
APS	aerodynamic particle sizer
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
BAECC	Biogenic Aerosols − Effects on Clouds and Climate
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CAPS	cavity attenuated phase shift
CARES	Carbonaceous Aerosol and Radiative Effects Study
CCN	cloud condensation nuclei
CCNC	cloud condensation nuclei counter
CDCE	composition-dependent collection efficiency
CFDC	continuous flow diffusion chamber
CIMEL	Cimel sunphotometer
CIMS	chemical ionization mass spectrometer
CIP	Column Intensive Properties Value-Added Product
DOE	U.S. Department of Energy
DOI	Digital Object Identifier
DQO	Data Quality Office
E3SM	Energy Exascale Earth System Model
ECAC	European Centre for Aerosol Calibration
ENA	Eastern North Atlantic
GASSP	Global Aerosol Synthesis and Science Project
GAW	Global Atmosphere Watch
GCM	general circulation model
GoAmazon	Observations and Modeling of the Green Ocean Amazon 2014/15
HI-SCALE	Holistic Interactions of Shallow Clouds, Aerosols and Land Ecosystems
HSRL	high-spectral-resolution lidar

HTDMA	hygroscopic tandem differential mobility analyzer
IMPROVE	Interagency Monitoring of Protected Visual Environments
INP	ice nucleating particle
IOP	intensive operational period
IPCC	Intergovernmental Panel on Climate Change
LT	long-term
MFRSR	multifilter rotating shadowband radiometer
MFRSR−7ch	multifilter rotating shadowband radiometer−7-channel
MPL	micropulse lidar
NASA	National Aeronautics and Space Administration
NEXRAD	Next-Generation Weather Radar
NILU	Norwegian Institute for Air Research
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSA	North Slope of Alaska
OSSE	Observing System Simulation Experiment
PI	principal investigator
PILS	particle-into-liquid sampler
PSAP	particle soot absorption photometer
PTI	photothermal interferometer
PTR-MS	proton transfer reaction mass spectrometer
QA	quality assurance
QC	quality control
RH	relative humidity
SASHE	Shortwave Array Spectroradiometer-Hemispheric
SBIR	Small Business Innovation Research
SGP	Southern Great Plains
SMPS	scanning mobility particle sizer
SOA	secondary organic aerosol
SP2	single-particle soot photometer
ST	short-term
TBS	tethered balloon system
TCAP	Two-Column Aerosol Project
TRACER	Tracking Aerosol Convection Interactions Experiment
VAP	value-added product
WCCAP	World Calibration Centre for Aerosol Physics
WCRP	World Climate Research Programme
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). 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 (https://www.arm.gov/publications/tech_reports/doe-sc-arm-tr-207.pdf), 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, 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. This report summarizes the second AMSG workshop conducted in November 2019 to advance a science-based strategy for ARM's aerosol measurement program. This workshop was built around themes that emerged over time from regular meetings of the AMSG and interactions at ASR-ARM meetings as topics with the greatest potential for high impact. Sessions held during the workshop focused on the following topical areas:

1. Interfacing with Models
2. Sampling Strategies and Site-Specific Measurements
3. Remote Sensing and Vertical Profiling
4. Aerosol Properties and Instrumentation
5. ARM Aerosol Calibration Protocols
6. Aerosol Data Products.

2.0 Framing Questions

Prior to engaging in detailed discussions in the above areas, workshop participants were asked to consider these topics from the perspective of developing science-based strategies relevant to the ARM user facility decadal vision and its impending update. The following framing questions were presented to engender this frame of reference throughout the workshop.

Who are the primary beneficiaries of ARM aerosol measurements? Are we appropriately serving these stakeholders and if not, how can we improve? Some key stakeholders identified were the ASR aerosol processes working group, scientists studying aerosol-cloud interactions in any of the ASR working groups, E3SM developers engaged in the implementation of aerosol processes, and scientists studying similar topics outside of ASR. While ARM data figures prominently in many studies undertaken by these groups, other aerosol research communities may benefit from ARM data but have not widely adopted its use, most notable the near absence of ARM data at the American Association for Aerosol Research (AAAR) or World Climate Research Programme (WCRP) Aerosol Comparisons between Observations and Models (AeroCom) meetings. Understanding why particular communities do not yet draw from ARM data resources might provide insight into directions for changing ARM science-based strategies for wider impact.

Is there a community strategy (or strategies) for linking ARM data to the representation of aerosols in large-scale models? Participants were encouraged to consider examples of how this has been approached in the aerosol community in the past and lessons learned, for example, regarding the Aerosol Modeling Testbed. It was noted that the Cloud Processes community has an established pathway for bringing ARM measurements to model representations – from observations to process models to single-column models and then to global circulation models (GCMs) – that should be considered.

To what extent is the current ARM sampling strategy a limitation to stakeholders? ARM's focus has traditionally been on long-term measurements (10+ years) at fixed sites (e.g., South Great Plains and East North Atlantic) and mid-term measurements (1-2 years) using mobile facilities (i.e., ARM Mobile Facilities or AMFs). However, previous surveys indicate that intensive ground- and aircraft-based campaigns result in greater community use and publication of ARM aerosol data. Such deployment strategy comparisons are instructive because they lead to important questions about whether the traditional supersite approach focused on a continuously operating central facility with a set of core measurements can answer priority aerosol-centric science questions. Approaches used during past campaigns (e.g., Observations and Modeling of the Green Ocean Amazon [GoAmazon 2014/15], Carbonaceous Aerosol and Radiative Effects Study [CARES], Two-Column Aerosol Project [TCAP], Biogenic Aerosols − Effects on Clouds and Climate [BAECC]) to merge advanced measurement systems from the community with ARM measurements have met with success. Upcoming AMF deployments to Houston for the Tracking Aerosol Convection Interactions Experiment [TRACER] and to the Southeastern U.S. provide near-term opportunities to further develop new or revise existing sampling strategies. Implementations specific to these campaigns will help guide general evolution of the ARM sampling and data development strategies into the future.

Does there remain a core set of operational and calibration issues with measurements and data processing that are a limitation to stakeholders? It is imperative to continue to evaluate whether users have access to well-characterized measurements in the most useful form. As measurement technologies and scientific foci evolve, the impact to stakeholder communities of implementing any given advancement must be considered.

Can near- and longer-term goals be devised for practical implementation of recommendations? Participants were asked to consider, given limitations in resources, practical approaches to what might be implemented in the next few years. Any near-term actions should be concrete enough to build a list of deliverables. At the same time, ARM encouraged workshop attendees to provide some vision for how the facility might evolve over the longer-term to best address the critical science in the coming decade.

3.0 Topical Discussions and Actions

The bulk of the workshop consisted of sessions in the six topical areas with the goal of developing science-based strategies relevant to the ARM user facility decadal vision and its impending update. Each session was opened by two co-leaders to provide an overview of the relevance of the topic to ARM specifically and the wider aerosol science communities in general and to present discussion points leading to discourse concomitant with the framing questions.

3.1 Interfacing with Models

While the aerosol properties measured by the AOS are fundamental to understanding aerosol processes and their representation in models, data formats are not always easily usable by modelers and inherent measurement uncertainties are not always communicated adequately. Modelers frequently use data sets from many sources and types of measurements for process module development and evaluation, and consequently have to familiarize themselves with a range of data formats. Further, it is of fundamental importance that there is physical self-consistency among these different types of measurements in their characterization of aerosol properties for useful implementation in model development and evaluations. To ensure physical self-consistency, closure studies are necessary for the data sets involved. An additional complication is that the development priorities for aerosol process modules and evaluation strategies of local, regional, and global modelers are not necessarily the same.

In this session, some of the issues associated with linking ARM aerosol measurements and modeling activities were discussed with the input from local, regional, and global modelers. Several short-term (ST) and long-term (LT) efforts were identified for ARM to consider:

ST1: Increase effort on aerosol data quality and consistency among disparate measurements
ST2: Increase effort on data products useful for aerosol modelers
ST3: Provide more detailed information about measurements and data-reduction strategies/protocols for modelers
ST4: Expand the number and type of aerosol modeling users
ST5: Assign someone to help link aerosol modeling and ARM observational communities

LT1: Focus on aerosol sampling during field campaigns
LT2: Optimize ARM data collection for model improvement
LT3: Develop size-resolved composition measurements

Short-term efforts: Data quality, as noted by ST1, was an issue frequently raised by workshop participants. Deriving parameters such as mean geometric particle diameter and creating unified size distributions obtained from several instruments with different approaches to sizing are examples of activities that could support ST2. Modelers likely do not fully grasp the nuances associated with operating instruments including measurement limitations, motivations, and the impacts of post-processing methodologies. Providing an executive summary for instruments and datastreams that contains only the most critical information for the appropriate use of the data would support ST3. Web page content and Data Discovery pathways specifically targeting aerosol modelers could be developed as part of ST4 along with organizing aerosol data bundles for model applications. In addition, making the aerosol data formats more consistent with other communities and engaging diagnostic tool developers could expand the number of aerosol modeler users. Finally, revisiting the idea of an aerosol modeling translator is a potential approach to address ST5.

Long-term efforts: ARM field campaigns have been highly successful for the aerosol community because a wide range of measurements are needed to constrain the development of aerosol process modules and rigorously evaluate model predictions. Therefore, this strategy should be continued as part of LT1. For LT2, ARM should consider developing a framework that supports Observing System Simulation Experiment (OSSE)-style model-driven studies that suggest optimal measurement strategies for field campaigns. Aerosol modelers frequently noted that size-resolved chemical composition measurements are needed to improve and evaluate the next-generation aerosol process modules (LT3). It was agreed that having this information available in just a few broad size bins may suffice for aerosol modelers.

The short-term and long-term efforts needed to produce high-level data products relatable to model input or output can be divided into four broad activities, including:

1. **Data Quality:** The quality of data from individual instruments is critical for modelers to determine whether aerosol predictions compare reasonably well to observations and whether modifications to aerosol parameterizations result in improved predictions. The accuracy and precision of particular observables should be assessed and documented, to benefit the entire research community.
2. **Data Set Self-Consistency:** The comparability or self-consistency among geophysical variables measured by different instruments is an aspect of data quality. Closure among measured aerosol properties is essential to build a reliable data set for model developers, identify reasons for lack of closure, define periods when measurements are inconsistent, and quantify the impact of measurement error among various instruments. Operational closure analyses, such as those for aerosol optical properties and cloud condensation nuclei (CCN), have been called for frequently. These closures would enable modelers to better assess predictions of direct and indirect effects of aerosols.
3. **Data Access:** ARM currently produces individual datastreams from distinct instruments, but modelers often prefer to have “data bundles” in which all relevant aerosol information is available as a single download and uses a common time interval. Since modelers often use observations originating from multiple sources, standards on reporting aerosol data and instrument calibrations similar to other organizations would be useful. ARM aerosol data could then be easily merged with data from other sources and thus would be more accessible and valuable to a larger user community (e.g., AeroCom, AirNow, Global Atmosphere Watch [GAW]).
4. **Diagnostic Tools:** Modelers typically need to develop additional software to enable direct comparisons of the available measurements with model output that contribute to performance metrics. This may be as simple as time-averaging an aerosol measurement (e.g., 1-s) to output and model time intervals (e.g., 1-h), or invoking more complex formulas and assumptions when a measurement is not directly comparable to a model parameter (e.g., differences in wavelengths used for optical properties; differences in supersaturation used for CCN; wet versus dry aerosol; ambient conditions versus reported values at standard temperature and pressure). Additional considerations may need to be made when comparing a point measurement with a model grid cell average. It is evident that clear communication of instrument/measurement properties is therefore essential for modelers to correctly use those measurements in their diagnostic tools.

Activities in these areas need to be closely coordinated with aerosol modelers such as those involved with the development and application of E3SM. While ARM should be largely responsible for activities 1–3, they are also critical for diagnostic tools that should originate from individual modeling communities with their own needs and objectives. For example, a few E3SM diagnostic tools already exist that use ARM data to quantify model performance; however, only a limited amount of aerosol data is currently being used. Support of efforts to modify those tools to include additional aerosol datastreams from routine and field campaign sources will be important. ARM could act as an intermediary by altering data structures to address modeler needs and sharing diagnostic tools among different organizations.

Further, many aerosol processes that currently require development for the sake of model improvement operate at very small scales compared to parameterized boundary-layer and cloud processes. ARM measurements tend toward bulk measurements that reveal processes occurring over a larger range of spatial scales. The aerosol chemical speciation monitor (ACSM) instrument is one example that provides bulk measurements of the primary accumulation-mode aerosol species needed to evaluate secondary organic aerosol (SOA) formation as well as processes contributing to diurnal and multi-day variations in total mass that influence aerosol optical and CCN properties. Determining how ARM and ASR can best bridge these spatiotemporal measurement gaps is critical for continued improvement of aerosol module treatments within Earth system models. The participation of measurement and modeling experts will be required to determine what is possible and how data can best be assembled and interpreted for these uses.

3.2 Sampling Strategies and Site-Specific Measurements

ARM currently supports three long-term observatories or "fixed" sites – Southern Great Plains (SGP), Eastern North Atlantic (ENA), and North Slope of Alaska (NSA) – three mobile facilities (AMF 1-3), and multiple aerial facilities (manned and unmanned aircraft and tethered balloons). Much effort has gone to determining the suite of measurements that comprise the AOS at each of these facilities (Appendix A), which are very similar for each site and run continuously at fixed sites and throughout campaign periods. However, much of current aerosol science is process specific and investigated through short-term intensive operation period (IOP) studies. Further, as noted above, 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. The Sampling Strategies and Site-Specific Measurements session centered on the distribution of ARM aerosol measurements in space and time. The session addressed issues such as: (1) whether the core set of measurements should continue to be made continuously at all sites, (2) whether complex ARM-owned instrumentation (e.g., particle-into-liquid sampler [PILS], proton transfer reaction mass spectrometer [PTR-MS]) and others not currently owned by ARM should be made available to run episodically, and (3) if an expanded and routinely available guest facility would encourage a useful suite of measurements. The discussion addressed how ARM can support the most relevant science being pursued by the community in the long term and what science can be done with the current ARM measurement strategy. The high-level short-term and long-term recommendations from this session are listed here and a complete list of recommendations from an interactive portion of this session are included in Appendix B.

ST1: When siting AMFs, consider the availability of airspace for unmanned aerial system (UAS) deployment.
ST2: When siting AMFs, consider local-source contamination and develop data quality flags for local-source influences at each ARM site.

ST3: Provide the core aerosol measurements at each site on the ARM instrument web pages.
ST4: Develop and publish aerosol instrument calibration and sampling protocols (follow national or international standards, e.g., European Centre for Aerosol Calibration (ECAC), when reasonable).
ST5: Link calibration and sampling protocols with data through improved metadata for aerosol instruments and measurements.
ST6: Characterize AOS inlet for coarse-mode particles.
ST7: Improve ARM translator-mentor communications, perhaps through an annual meeting, to review current measurements and data products (instrument status, up-time, calibrations) for data quality, accessibility, and the realization of value-added products (VAP).
ST8: Support direct collaborations between instrument mentors and vendors including key science users and translators.
ST9: Publish ARM-specific measurement science studies (often limited to ARM reports) in peer-reviewed literature when possible/appropriate.
ST 10: Implement hygroscopic tandem differential mobility analyzer (HTDMA) ambient ("scanning mobility particle sizer [SMPS] mode") scan where possible.

LT1: Develop 3-tier measurement strategy involving long-term observations, intensive periods, and guest instruments; delineate continuous measurements versus those only run during intensives (may be site dependent).
LT2: Consider running seasonal intensive operational periods (IOPs) at fixed locations with more complex ARM and guest instruments.
LT3: Continue to develop new measurement strategies, including vertical profiling, distributed networks, and expanded guest support.
LT4: Expand ARM's interface with external networks (e.g., National Aeronautics and Space Administration [NASA] Aerosol Robotic Network [AERONET], National Park Service [NPS] Interagency Monitoring of Protected Visual Environments [IMPROVE], Norwegian Institute for Air Research [NILU] EBAS, National Oceanic and Atmospheric Administration [NOAA] Federated Aerosol Network, AirNow).
LT5: Increase presence in the wider aerosol community (e.g., AAAR meetings booth, inclusion of more data in the Global Aerosol Synthesis and Science Project (GASSP) and World Meteorological Organization (WMO) databases, representation at AeroCom workshops, participating in measurement intercomparison studies).
LT6: Routinely conduct instrument intercomparisons and closure studies at all ARM sites.
LT7: Consider routine (e.g., bi-weekly) flights between SGP and SE U.S. AMF3 site.
LT8: Increase frequency of ice nucleating particle (INP) measurements, consider continuous measurements.

Shifting to an IOP mode of operation: Shifting the ARM aerosol sampling strategy was a major topic of discussion at the workshop, reflecting a larger discussion that has been growing in the community. The sentiment was that IOPs – annual, bi-annual, or seasonally – would serve to fill out the AOS measurement complement with detailed and process-specific measurements by using more complex ARM-owned instrumentation and guest instruments on an intermittent basis rather than a simpler instrument complement on a continuous basis. IOPs at long-term sites, and within AMF campaigns, could be targeted to address priority science objectives and could be proposal driven. A mechanism for principal investigators (PIs) to propose ARM small field campaigns during themed IOPs could produce substantial measurement efforts around critical science topics that the AOS alone is not fully suited to address. This would require infrastructure for guest measurement accommodations, and mentor attention ensuring that instrumentation is running during the IOP period.

Certain baseline measurements should remain in the current mode of continuous operation for their value in providing context for aerosol properties and their variability interannually and across the annual cycle. An additional suite of more intensive measurements could be deployed during IOPs (Figure 1). This mode of operation may generate greater interest across aerosol process research science and would benefit by direct modelers' input during planning stages and provide motivation for the modeling community to focus on common data sets. Specifically, a subset of the subscribed IOPs would focus on process questions, closure studies, or instrument comparisons. This shift would have the benefit of enabling mentors to structure their time differently, spending targeted periods in the field to ensure optimal operation during the IOPs and developing better understanding of measurements and the implications of their limitations, calibration, and data analysis in the interim periods between IOPs. A shift to this mode of operation would require identifying core measurements by site (it is assumed that they will differ geographically and according to science objectives) to run continuously and to serve as a baseline for the IOPs. Additionally, the timing of IOPs should be designed to augment core measurements in a seasonal-specific methodology, where, again, the selection of times should be driven by site-specific science desiderata.

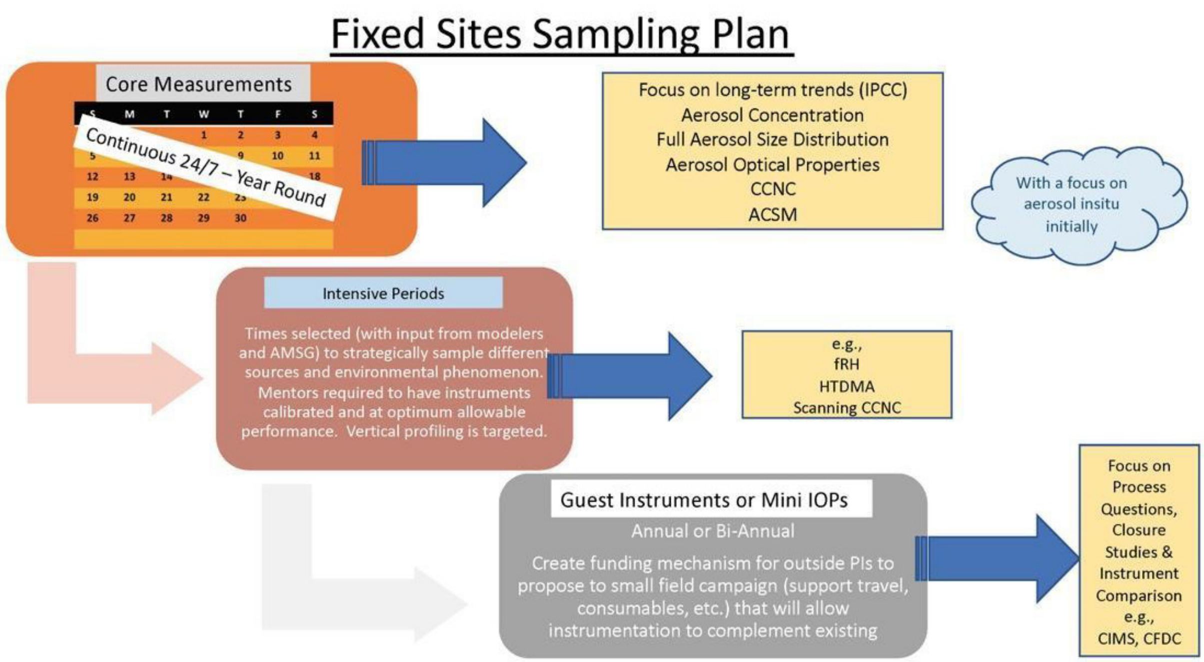

Figure 1. Diagram of ARM observatories aerosol sampling plan.

Enabling spatial and vertical sampling: The ARM measurement perspective began with a preponderance of aerosol, cloud, and radiation measurements in a single atmospheric column with a system of basic radiation measurements distributed over a model grid cell-sized area measuring continuously through time. Since then, the approach has been reorganized to provide measurements over a process model-domain sized area; however, the complexity of the AOS makes it difficult to distribute aerosol measurements. Regardless, 4D data (especially size and optical properties) are needed for model evaluation and development. Enabling spatial and vertical sampling through new measurement technologies should be a near- and long-term goal for the ARM facility. This would entail small sensor packages targeted for informing particular processes to be deployed on aerial platforms or distributed in the spatial domain. ARM should also continue to develop novel airborne platforms for vertical profiling. In situ measurements in the vertical are necessary to build improved remote-sensing retrieval algorithms that will ultimately provide temporally continuous and spatially distributed information on aerosol properties required for detailed process studies and by models for ensuring representativeness over the model grid cell or domain.

3.3 Remote Sensing and Vertical Profiling

Increasing the impact of ARM AOS measurements requires that the available data sets be in a form that allows for broad use in the analysis and modeling communities, necessitating the scope to answer a range of questions relevant to aerosol physical, chemical and radiative processes. Thus, detailed information from surface in situ measurements must be relatable to the ambient atmosphere. ARM has an extensive history of deploying passive and active remote sensors with application to aerosol property retrievals for vertically integrated and resolved ambient atmospheric column measurements. However, these data have not been fully exploited to provide synergy with the ground-based in situ measurements. Efforts to take advantage of the large amount of existing data from commonly deployed remote-sensing instruments and their associated long-term data records (e.g., multifilter rotating shadowband radiometer [MFRSR], micropulse lidar [MPL]) should be prioritized. Investing in a rigorous and internally consistent processing – ensuring closure among the retrievals from various instruments and consistency with in situ measurements – for these data would greatly increase the usability of data for analyses and modeling efforts.

In situ measurements on unmanned platforms are key to evaluating remote-sensing products as well as for characterizing vertical aerosol structures and their relationships to the same properties measured at the surface. Planning for campaigns in which the appropriate remote-sensing and airborne assets are deployed in a manner that lends itself to using these data sets together is encouraged.

ST1: Provide the Column Intensive Properties (CIP) VAP for all ARM MFRSR data.
ST2: Evaluation of the comparability between aerosol property retrievals from multiple passive sensors (MFRSR, Cimel sunphotometer [CIMEL], others as available).
ST3: Develop a plan for providing or improving extinction profiles from multiple lidars.
ST4: Develop plan for high-spectral-resolution lidar (HSRL) + Raman lidar + passive retrievals to provide vertically resolved aerosol size and absorption not achieved with other methods.

LT1: Develop an integrated plan for profiling that considers available ground measurements, active and passive remote sensing, and aerial measurements, especially tethered balloon system (TBS) and UAS.
LT2: Improve data logging for TBS (onboard) and integration of datastreams to increase ease of data use.

The data records from the MFRSR, CIMEL, MPL, and Raman lidar each span more than two decades. Over the last decade ARM has deployed MFRSR−7ch, shortwave array spectroradiometer-hemispheric (SASHE), MPL, and HSRL. Each of these existing datastreams can provide valuable information for aerosol studies but may be underused due to questions about data quality consistency and the availability of high-level data products. Efforts should be devoted to improving data quality and measurement confidence (may simply require data assessment and addition of flagging in metadata), and in implementing retrievals both for existing archives held by ARM and for new advanced technologies currently becoming available (e.g., Doppler lidar, updated HSRL). Comparisons, closure experiments (demonstrating agreement between measurements and model, or between one type of measurement and another), and evaluation of new measurement approaches should be a focus. Examples of comparison studies could include evaluation of extinction profiles from MPL with independent retrievals from Raman Lidar or HSRL, or closure of the retrieved extinction profile with measurements of aerosol optical depth (AOD) from surface radiometers. Comparison studies would provide comprehensive evaluation of remote-sensing measurements, define uncertainties, and could identify data epochs for further study. HSRL at least allows for direct evaluation of MPL extinction profiles due to having the same/similar wavelength. We believe the collocation of MPL and HSRL would go a long way to 1) improving/assessing MPL performance and 2) quantifying how accurate/reliable the MPL extinction is or can be.

Aerosol absorption continues to be both a large source of uncertainty in aerosol radiative effects and difficult to measure with desired accuracy. No standard in situ measurement for aerosol absorption currently exists and development or adoption of new methodologies has been slow. The role that remote sensing can play in characterizing aerosol absorption should be considered. Some studies for comparison of in situ and remote sensing aerosol properties exist (Shuster et al. 2019, Pistone et al. 2019). Using these as a model, ARM should explore the ability of their commonly deployed remote sensors, MFRSR and AERONET/CIMEL, compare with in situ measurements, and provide information on aerosol absorption in their own right. The very recent upgrade of the ARM MFRSRs to add a longer-wavelength channel may provide improved retrievals of aerosol optical properties and should be explored.

3.4 Aerosol Properties and Instrumentation

The instrument complement for aerosols deployed by ARM in the AOSs (Appendix A) is intermittently reviewed by the AMSG and with regular feedback from the user community with the goal of addressing science questions within the analysis and modeling communities. These reviews result in recommendations to add or change measurements, transition away from instruments that are no longer supported by vendors or the community, and to sunset existing instrument systems that do not meet these goals. In some cases, ARM has fielded new instruments that have not yet been well characterized but hold promise for filling critical measurement gaps. Given its existing extensive instrument deployment, ARM is uniquely positioned to evaluate new technology in the context of co-located complementary measurements. These issues were discussed in depth during the 2017 AMSG strategic planning workshop and were the focus of the resulting implementation plan. However, since then new instrumentation issues have arisen and others that were discussed but have not been addressed have risen to high priority. Recommendations from a continued discussion at this workshop for aerosol measurements include:

ST1: Active support for the publication of measurement science papers as they relate to ARM aerosol instrumentation.
ST2: Develop a path forward for replacement of the discontinued particle soot absorption photometer (PSAP).
ST3: Implement an improved inlet drying method across ARM observatories.
ST4: Implement flow scanning for the CCN.

LT1: Assess implementation of additional humidigraphs.
LT2: Reconcile different size distribution measurement methods and datastreams in a single, accessible data product.
LT3: Facilitate increased interaction among PIs and mentors regarding configuration of complex instrumentation.

ST 1: In many of the workshop sessions, the benefit of providing peer-reviewed publications characterizing ARM aerosol measurements and data products to increase user confidence and understanding of the data was expressed. ARM mentors regularly work at every stage of the measurement process − from sampling to instrument configuration, operational modes, calibration, and data reduction algorithms − and also work with vendors and end-users to improve measurement and data processes. These improvements should eventually work their way back to operational ARM processing and data product development. Access to this work done in the peer-reviewed literature (rather than only from DOE-published reports) improves the visibility of the work and eases the process of referencing and disseminating the information broadly.

ST 2: The AMSG and aerosol science community agree on the importance of absorbing aerosol measurements and once again emphasized its priority: thus, ARM will continue in situ measurements of absorbing aerosols. However, the PSAP, deployed since the inception of ARM aerosol measurements, is no longer manufactured and individual units may be reaching end of life. Commercial alternatives need to be evaluated – the most viable being the AE-33 aethalometer – but the AMSG encourages consideration of newer-generation approaches such as the photothermal interferometer (PTI) that will likely be widely deployed in the future due to its direct absorption measurement approach and superior characterization for absorbance.

ST 3: Uniform drying of the air sample for AOS measurements is critical for achieving a defined size cut at the aerodynamic impactor, for ensuring consistency in size and optical property measurements, and to prevent sample-line condensation in high-humidity environments. Heating the inlet to reduce relative humidity (RH) was used in earlier AOS systems but was universally agreed to be undesirable. While the idealized goal is a uniform 35% RH throughout the AOS sample lines, it is also recognized that the RH must be monitored everywhere within the AOS (e.g., prior to the 1- and 10-µm impactor, in front of instruments measuring optical property, etc.). Preliminary field work carried out at SGP suggests even more that drying air will be required, and further evaluations are scheduled during the summer of 2020. The additional drying will be required for high-humidity environments such as SGP in the summer and notably for the upcoming TRACER campaign in Houston, Texas and AMF3 deployment to the Southeastern U.S. Several strategies are being adopted. The AMSG stresses here that implementing uniform drying across all AOS is essential for intercomparability of aerosol properties across sites and the closure studies that have been called for in various discussions during the workshop and beyond.

ST 4: Several discussion groups of end-users and measurement experts have advocated changing the supersaturation scanning mode of ARM CCN instruments. As presently implemented, a full supersaturation scan using temperature takes over 30 minutes and there is dead time for equilibration between supersaturation steps. Flow scanning has been shown in preliminary field experiments to be considerably faster such that the entire scan can be related to the same aerosol population. Different modes of operation (scanning rates and ranges) were suggested during IOPs similar to radar scanning strategies used to meet IOP priorities.

LT 1: ARM currently operates 4 f(RH) systems in which a controlled, scanning, humidification section is situated between two nephelometers operating in series. Recommendations for additional humidgraphs will be weighed against the similar growth factor measurement from the HTDMA. Modelers need the specific change in optical scattering with humidity, but this information can be inferred from physical growth factors and Mie scattering theory. The chemical information that can be gleaned from f(RH) measurements is important, but this measurement is expensive and logistically complicated. Ambient (or reference dry) scattering measurements will be needed regardless.

LT 2: Another ongoing conversation regards developing a value-added size distribution data product largely geared to the modeling community. As described above, aerosol size distributions are measured in the AOS over a wide range of sizes using different instrumentation and measurement approaches for different size ranges. The modeling community requires a distribution across this range that is consistent in sizing approach and unit of measure. The ARM Aerosol Developers and VAP Translator group is nearing completion of an effort to harmonize APS, UHSAS, SMPS, and nano-SMPS datastreams. This will put the four datastreams on a common format of bin descriptions, units, time, and diameters, among others. A separate team of mentors is looking at how to merge the size distributions over this range to resolve (or at least bound) different measurement principles, different counting efficiencies, and different sampling conditions (clarify how these two steps in the process differ). This resolution effort will require a combination of laboratory and field measurements and is thus a longer-term project but a high priority for the aerosol community.

LT3: The configuration of some instruments in their sampling parameters or in the way multiple instruments are related to each other in a sampling pathway may provide the ability to derive a wider range of information or geophysical variables than if the instruments were run separately. Involving Mentors with PIs at the early stage of IOPs to guide sampling strategies can improve outcomes in terms of information content of aerosol properties and process evaluation.

3.5 ARM Aerosol Calibration Protocols

To build trust in ARM aerosol measurements with the global research community, a first-order requirement is to maintain an accepted and well-documented protocol for instrument calibration and characterization, using accepted protocols and world standards where possible. Additionally, there is an ongoing need for developing particle standards of known size, shape, and composition to improve measurement and model performance and for calibration. This session was devoted to the discussion of recent efforts taking place within the Aerosol Processes Working Group that involve bringing together theorists, modelers, and experimentalists in order to articulate needs for new types of aerosol standards that will both aid in interpreting laboratory and field measurements as well as assure that those measurements address the needs of models. This effort has culminated in a white paper (https://tinyurl.com/particle-standards) that presents calibration and standards approaches that could be employed in the near term with established technologies as well as identifying new types of standards for further development. The report comprises six chapters, each devoted to a specific measurement of importance in atmospheric aerosol research (authors noted in parentheses):

1. Aerosol Size Distributions and Number Concentrations (Kuang)
2. Species-Resolved Mass Concentration Standards for Aerosols (>50 nm) (Canagaratna, Croteau, Gaston, and Jimenez)

3. Species-Resolved Mass Concentration Standards for Aerosols (<50 nm) (Smith and Johnston)
4. Soot Particles (Onasch, Sedlacek, Lewis, Cappa, Feng, and Chakrabarty)
5. Particle Hygroscopicity: Water Uptake and CCN Measurements (Petters)
6. Aerosol Standards for Ice Nucleating Particle Measurement Methods (DeMott)

The AMSG stressed the importance of continuing this work and made the following related recommendations specific for ARM measurements.

ST1: Direct engagement with World Calibration Centre for Aerosol Physics (WCCAP).
ST2: Improved communication on which ARM instruments follow and do not follow international protocols (move to such protocols where we are not).
ST3: Following comment period, begin tracking versions of calibration whitepaper made available to the ARM user community.
ST4: Identify targets for characterizing measurement uncertainties:

- Uncertainties report (Sisterson): https://www.arm.gov/publications/programdocs/doe-sc-arm-17-010.pdf
- Translator plan (Riihimaki; including uncertainties section): https://www.arm.gov/publications/programdocs/doe-sc-arm-17-039.pdf

The white paper will be condensed and published in a peer-reviewed journal in fall 2020.

European efforts in this area such as the World Calibration Centre for Aerosol Physics (WCCAP) were also discussed. WCCAP is quite open to collaborating to harmonize calibration standards internationally. The presentation ended with discussions on three points: With regards to the "established calibration methods," should DOE require that they be used for DOE-funded research? What can DOE do to help DOE-funded researchers with such QA work in the field? With regard to standards and calibrations that require further work, should DOE establish the expectation that some effort in DOE-funded experimental projects would focus on standards and reducing measurement uncertainties? Finally, since the cost of instruments and facilities needed for instrument calibration is a common theme in the white paper, this suggests the need for centralized facilities. Is it possible for the DOE community to establish such a facility?

3.6 Aerosol Data Products

ARM has made substantial progress in improving the quality of aerosol data products available to the user community. The AMSG helped define the initial recommendations for data products improvements and continues to be a key contributor for driving data product recommendations for both basic ingests and VAPs. Harmonization of the aerosol datastreams began in 2014 and a majority of the instruments have b-level data products which implements calibrations, corrections, and added quality control checks (See Appendix C for a list of all aerosol datastreams in each processing level). Five of the remaining b-level datastreams are planned for FY20. Proper documentation of the a1-to-b1-level processes for each of these instruments is necessary to create transparency for the user community. There is also an ongoing effort to bring the single-particle soot photometer (SP2) processing into ARM in an automated and open-source manner. Some specific data products and general operational procedures were recommended to meet the near-term needs of the aerosol process research community.

ST1: Develop methodology to track instrument issues in a more quantitative way.
ST2: Complete processing system for ACSM.
ST3: Implement CCN kappa product.
ST4: Develop an evaluation product for a merged aerosol size distribution.
ST5: Implement multi-instrument CCN profile VAP, starting with the Holistic Interactions of Shallow Clouds, Aerosols and Land Ecosystems (HI-SCALE) period at SGP.
ST6: Work with ARM Metadata team to improve aerosol recommended datastreams.

As aerosol harmonization, QA/QC protocols, and new end-user data product development progresses, the resulting data must be clearly described and changes delineated with the information readily discoverable by the user community. With recent changes to the entire aerosol data file structures, such discovery within the ARM Data Center is difficult. Documenting the explicit organization of aerosol data files and ensuring that useful metadata is associated with each product it is expected to improve data discovery within the ADC. The metadata team will be reviewing the recommended aerosol datastreams with the aerosol translator who will solicit feedback from the AMSG and broader scientific community to improve the recommendations. These recommendations dictate how datastreams are displayed in Data Discovery and will lead to a better user experience.

4.0 Principle Cross-Cutting/Workshop Conclusions

Following the topical sessions, a "synthesis" session was held on the final day of the workshop. The major recommendations that arose from each of the sessions were reviewed, commonalities across the different themes were examined, and the group was asked to express some qualitative prioritization of recommendations taken as a whole. High-level and cross-cutting needs for implementing a science-oriented strategy for ARM self-organized into actions that could be taken in four general areas: 1) data quality, 2) measurements, 3) sampling, and 4) data usability. To help move toward an implementation plan for ARM aerosol measurements, these summary recommendations are described in this section.

4.1 Data Quality

Data quality is the foundation on which all other ARM services rest, and thus priority should be given to addressing these needs. Three general areas for promoting enduring and pervasive improvements to data quality were emphasized.

- **Shifting mentor time from the field to the laboratory and to time spent analyzing data** would improve ARM data quality. This objective is related to another recommendation to focus on intensive measurement periods rather than continuous operation of all aerosol instrumentation, outlined in Section 3.3. Facilitated by more time between intensive operational periods, mentors would have their instruments in the laboratory for more frequent hands-on calibrations (Section 3.5) and maintenance. Focus on these intensives rather than continuous operations would also provide mentors the time for data analysis, involving mentors in the timely use of the data as a prefatory inspection of the data beyond the scope of the Data Quality Office (DQO) and to promote good and responsible use of the data thereafter. The latter can contribute to a better connection between the instrument operation and high-level data products that are needed for modeling and process studies (Section 3.1.) To preserve mentor time for calibrations, maintenance, and analysis, ARM could consider teams of science and technical mentors for instruments that require more attention. The proposed shifting of mentor time would also have the added benefit of professional development through publication of peer-reviewed measurement science papers.

- Investment in **developing established calibration protocols and more frequent participation in national and international instrument intercomparisons** to ensure the most accurate measurements in the field is critical. Mentors would require support for their time to participate in these activities. To streamline the processes in the long term, ARM should consider establishing a U.S.-based calibration facility for its aerosol instrumentation, drawing from European experience, that could also serve other U.S. organizations.
- **Closure experiments** among the parameters measured in the AOS is considered a fundamentally important objective check on the quality and physical validity of the measurements. The AOS is designed to explore the relationships among aerosol microphysical, chemical, and optical properties, and as such, all of the observables are related in some way by theory. A range of closures can be performed using existing data sets that would call attention to inconsistent measurements or periods of poor data quality. Additional advantages of the closures are the improved understanding of the measurements, their basic contribution to physical interrelationships of the observables, and how they relate to physical and theoretical understanding of the atmospheric radiation budget. ARM, or potentially ASR, should consider supporting the design of closure exercises and operationalizing some of these exercises for the DQO and mentors to monitor routinely.

4.2 Measurements

While the prioritization of different measurement classes and instrumentation was the focus of the 2017 workshop, specific measurement challenges remain that serve as obstacles to ARM and ASR science foci. The following recommendations were made within the key measurement classes.

- Given the difficulty in measuring absorption in situ, improve the **use of remote sensing to constrain aerosol absorption**. This would include building the MFRSR Column Intensive Properties (CIP) VAP when and where possible for the large archive of data and developing a new algorithm for the new wavelength-extended MFRSRs. Raman lidar data, where available, should undergo quality checks and data epochs developed to provide users with target data sets for improving understanding of processes related to aerosol absorption. Retrieval algorithms for the HSRL and synergistic measurements (passive radiometry) should be developed. Within the AOS, the use of extinction measurements (cavity attenuated phase shift; CAPS) should be considered in how they can be used with scattering and absorption measurements to constrain absorption in situ.
- **Measurements of cloud condensation nuclei (CCN)** have been identified as a priority for aerosol and aerosol-cloud interaction science. Current operational protocols for the CCN involve temperature scanning for producing CCN number-supersaturation spectra. A **flow-scanning method** has been implemented and tested both in the laboratory and at SGP that would improve temporal resolution and accuracy at low supersaturation, but a report from the more comprehensive field demonstration project is needed to prepare for shifting all ARM measurements to flow scanning.
- ARM has acquired new aerosol **humidification measurement** instrumentation and has extended appreciable effort in establishing their robust operation. These instruments are highly flexible in their

potential configurations and the data products they would allow. Preferences for **particular measurements, their operational configurations, and data products** for end-user access need to be defined.

- Size distribution has been determined as the most fundamental aerosol measurement need for ARM sites. **A publication that presents an evaluation and comparison of the SMPS and UHSAS** is needed to guide data use and improve trust in ARM size distribution measurements. (include full range of measurements: APS, CPCs, and closure).
- In addition to investing in ACSM operations, ARM has implemented IMPROVE monitoring of **aerosol chemical composition** at SGP recently. A **strategy for providing the appropriate components of composition at the right scales** should be pursued. Ultimately, modelers require **size-resolved chemical composition** to fully inform model evaluation. This measurement is exceedingly complex but has been persistently raised as a need, so ARM should consider it as a long-term goal.

4.3 Sampling

Shifting ARM sampling strategy was a major topic of discussion at the workshop, reflecting a larger discussion that has been growing in the community.

- Continuous operation of the large suite of aerosol measurements at each site is resource intensive. This resource-intensive requirement, combined with the publication evidence that intensive measurement periods that provide more comprehensive and detailed observations through guest instrumentation are better used by the community than long-term data records, leads us to recommend **shifting to an IOP mode of operation**. IOPs at long-term sites, and within AMF campaigns, could be targeted to address priority science objectives and could be proposal driven. We believe that this mode of operation would generate greater interest across aerosol process research science and would provide motivation for the modeling community to focus on common data sets. This shift would also allow mentors to restructure their time, spending targeted periods in the field to ensure optimal operation during the IOPs and focusing on instrument maintenance, calibration, and data analysis in the interim periods (Section 4.1). Related is the need for identifying core measurements by site (it is assumed that they will differ geographically and according to science objectives) to run continuously and to serve as a baseline for the IOPs, the need for facilitating the deployment of more complex aerosol instrumentation that is ARM owned, and support for guest instrumentation to fill measurement gaps.
- The ARM measurement perspective began with a preponderance of cloud and radiation measurements, with aerosol measurements added later, in a single atmospheric column with a system of basic radiation measurements distributed over a model grid cell-sized area measuring continuously through time. Since then, the approach has been reorganized to provide measurements over a process model-domain sized area. However, the complexity of the AOS makes it difficult to distribute aerosol measurements. Regardless, 4D data (especially size and optical properties) are needed for model evaluation and development. **Enabling spatial and vertical sampling** through new measurement technologies should be a near- and long-term goal for the ARM facility. Small sensor packages targeted for informing particular processes could be deployed on aerial platforms or distributed in the spatial domain. ARM should also continue to adopt novel airborne platforms for vertical profiling. In situ measurements in the vertical are necessary to build improved remote-sensing retrieval algorithms

that will ultimately provide temporally continuous and spatially distributed information on aerosol properties required for detailed process studies and by models for ensuring representativeness over the model grid cell or domain.

4.4 Data Usability

The AMSG has acknowledged the importance of data accessibility and usability for building a stronger user base and to meet the needs of modeling. Several activities were identified that would aid usability:

- **Operational closures** as discussed above to ensure data quality and consistency among measurements (intercomparability) for use with models.
- **Data bundling** of high-level data products for model diagnostics could make use of a framework structured for IOPs (described above) that would aid in access to the data for analysis and modeling.
- Uniform reporting of **size distributions** across size ranges measured, with at least a guide for how to interrelate size measurements from different instrumental techniques.
- **Post-processing masks** for removal of contamination periods or sorting based on wind direction for sector control.
- **Publication of ARM-specific studies, calibration protocols, sampling strategies, and technical aspects of the measurement science** that has been undertaken to develop ARM data products would provide easy reference to data characteristics and reliability. (*Earth System Science Data Journal* recommended.)
- Better and more frequent **translator-mentor communication** along with instrument vendors where appropriate would expedite development of priority data products. (Consider an annual meeting in tandem with the mentor meeting.)
- Additionally, **mentor-user web conferences** might be considered to raise the visibility of mentors and to ensure more responsible use of data.
- **Improve instrument pages on the ARM website and link to Data Discovery** to convey recommended data and available products and their characteristics. Aerosol scientists should participate in Data Discovery evaluation and development exercises, visualization of data, and identification of recommended datastreams.
- **PI data product submissions should be encouraged** to maintain a pipeline of relevant VAPS and, where appropriate, open source codes for development by the larger community.

5.0 Current and Future Actions

The AMSG workshops have been designed to inform actions that ARM can take or support in order to enable the evolution of the facility to continue to meet its mission. To advance that process, the AMSG will follow up on developing an actionable plan from the recommendations outlined in this document. Some recommendations are well defined and can reasonably be accomplished in the short term. Other recommendations are less definite or of a larger scope that will call for a longer-term implementation. Further discussion will be required to develop and prioritize actionable items related to these areas that are not currently well defined. Task teams comprising the appropriate expertise and perspective from the

AMSG and other members of the community will be formed to achieve this. Appendix D contains tables of all recommendations from the workshop that can be used in developing action plans.

Some particular topics are recognized to have high priority and so plans are currently underway to develop task teams and to have follow-on discussions to address them. Four areas currently being considered for short (one half- to one-day) focused discussion are 1) aerosol measurements on the North Slope of Alaska, 2) improving data useability for modeling, 3) strategies for advancing remote-sensing, vertical profiling, and distributed measurements of aerosol to complement AOS measurements, and 4) aerosol sampling strategies at existing ARM sites to provide intensive modes of operation to promote data usage for process and modeling studies. ARM is in the process of withdrawing the AMF3 observatory from Oliktok Point, Alaska for deployment in the Southeast U.S. While limited aerosol measurements have been supported at the NOAA Barrow Observatory in Utgiagvik over several decades, ARM has not made in situ aerosol measurements at its North Slope of Alaska site on the same order of other sites. Given the importance and intensity of changes in Arctic climate the community has expressed strong support for increasing the measurement complement there. Further, NOAA is currently constructing a new, state-of-the-art scientific facility at the Barrow Observatory with an aerosol inlet and increased space for instrumentation. DOE and NOAA intend to collaborate in this effort and a planning discussion will be scheduled in the fall of 2020. In the first half of 2021 the AMSG intends to host a discussion to address the other three topics.

Finally, the AMSG and ASR Aerosol Processes Working Group have been increasingly interacting to address the more science-based issues that are currently the focus of this group. Putting the recommendations made here in the context of the ASR science team's critical science questions may help prioritize actions by assessing a number of elements related to those questions. The Cloud Processes Measurements and Science Group has begun to construct matrices around science questions that consider problems and roadblocks related to the science, the impact of addressing those roadblocks, the research elements involved, the maturity or readiness of the solution, a definitive description of the solution itself, and a potential roadmap to bringing the issue to the realm of modeling. In the next several months, we intend to construct matrices with these elements for priority science questions guided by the APWG.

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Appendix A

AOS Measurement Complement by Site

AOS Instrument Complement

Last Revised: V1.14, 11/09/2019

Instrument	AMF1 AOS01 [*1]	AMF2 AOS02	AMF3 AOS03	ENA AOS06	SGPE13 AOS07
ACSM/Q - Aerosol Chemical Speciation Monitor - Quadrapole					
ACSM/TOF - Aerosol Chemical Speciation Monitor-Time of Flight		Guest for MOSAiC	removed for MOSAiC		
Aethalometer					
APS - Aerodynamic Particle Sizer					
CAPS - Cavity Attenuated Phase Shift Monitor					
CO - Carbon Monoxide/Nitrous Oxide/Water Vapor					
CCN - Cloud Condensation Nuclei	CCN-200	CCN-200	CCN-200 non winter	CCN-100	CCN-200
CPC - Condensation Particle Counter					
µCPC - Ultra-Fine Condensation Particle Counter					
GHG - Green House Gases (CO2, CH4))					
HTDMA - Humidified Tandem Differential Mobility Analyzer			non winter		
1- 10-µm Impactor					
n-SMPS - Nano Scanning Mobilty Particle Sizer					
Neph, Amb - Nephelometer, Ambient					
Neph, Dry - Nephelometer, Dry RH Scanned		Broken			
NOx - 3 Channel: NO, NO2, NOy					
O3 - Ozone					
PASS-3 - 3 Wavelength Photo Acoustic Soot Spectrometer *2	sunset				sunset
PILS - Particle Into Liquid Sampler					
PSAP - Particle Soot Absorption Photometer					
PTRMS - Proton Transfer Reaction Mass Spectrometer					
SMPS - Scanning Mobility Particle Sizer		Guest for MOSAiC			
SO2 - Sulfur Dioxide					
SP2 - Single Particle Soot Photometer		Guest for MOSAiC			
TAP - Tricolor Absorption Photometer					offline
UHSAS - Ultra High Sensitivity Aerosol Spectrometer					
WXT520 – Weather Sensor					

Legend	
Part of System	
Not part of System	
Part of System, not yet Delivered	
At site but not installed in AOS	
Currently needs replaced	

Notes

*1 Original AMF1 AOS00 was mothballed as of 12/1/2015. It is formally replaced by AMF1 AOS01.

*2 The PASS-3 was sunset on 10/1/2015.

Appendix B

Survey Results from Sampling Strategies Discussion

Recommendation #1: Select the new SE U.S. ARM site to be isolated from local sources, with open airspace for vertical profiling, and on a site with potential for wide-area network.

1. SE ARM site recommendation: well sampled by a nearby Next-Generation Weather Radar (NEXRAD) radar.
2. Automated, multi-parameter processing needed.
3. Isolated site appropriate for regional studies, but some studies are focused on local emissions.
4. We should always strive to be isolated from local sources, but logistics have a big say as well.
5. Coupling of rich short-term data sets with long-term measurements is often very useful.
6. SE U.S. ARM site recommendation: find local partners (e.g., Huntsville laboratories).
7. Should have space and infrastructure for guest instruments/PIs.
8. A GCM grid-cell-sized area with distributed measurements that can constrain the budget of aerosol (what moves in and out) of the area.
9. Ideal ASR mission site would be regionally representative. But ideal is seldom achievable (exception was the All-Sky Imager, which was close to perfect). If not ideal, site should have well-defined local sources that can be masked.
10. As far as distributed measurements, that is a moving target. Climate models are going to smaller and smaller Dx. The SGP is set up for a 100-km cell, but how to define a long-term solution to spatial variability?
11. Crucial for SE U.S. ARM site is supporting measurements, i.e., at an existing site run by collaborations.
12. Yes, but devil is in the details.
13. SGP is often not viewed as a “good” site for aerosols but I think the problem is a lack of salesmanship. In fact, aerosol processes can be studied in many places, and this infrastructure is very useful.

Recommendation #2: Need to define the core measurement list for AOS systems within ARM and detail instrument calibration and sampling protocols.

Comments on communication of core measurements:

1. Metadata on instrumentation is historically challenging.
2. Duplicates are recurring zombie metadata problems.
3. It seems to me like this is already done, just needs to be better communicated.
4. Would a 'user-centered' redesign (by a cross-functional team) help with producing an interface to the ARM data that user finds more useful?
5. Baseline does not mean core necessarily. It's mainly that it's an operational instrument in ARM.
6. This seems like it's mainly a communications and metadata issue.
7. Core measurements should be the easiest to define and communicate with the community. If that is confusing, then anything else is even more confusing.
8. Communicate the uncertainty that is known.
9. We need a two-layer system. One simplified overview of what is available and then something with the details. They should be linked.

Instrumentation suggestions for core measurements:

1. We can scan supersaturation at all but one CCN station.
2. Better and more frequent measurement of RH within the AOS sample lines.
3. ARM is well positioned to do more long-term measurements of aerosol size distribution, CCN, and INP, which are still relatively rare and would be more useful for evaluating/constraining aerosol-cloud-climate models (compared with AOD, PM2.5, etc.)
4. A direct measurement of aerosol absorption.
5. Shorter wavelengths for optical properties that can describe characteristics or organic aerosols.
6. A lot of what was shown was all metadata related. Things have been guest at one point and have become baseline. That is why some are listed as both. It's not what it is currently, but what happens over time.
7. APWG survey #3: CCN concentration at different supersaturation.
8. From a CCN perspective, quantification of mixing state is probably most useful in marine locations (since continental aerosol is rapidly internally mixed). Are there other questions where it is useful?
9. Can you provide a single file for each property that modelers could use? E.g., a single netCDF or .csv file of aerosol size distribution data from all of the deployments where it has been measured and QCd.
10. APWG survey #2: Composition information beyond ACMS.
11. APWG survey #5: Aerosol surface area retrieval.
12. APWG survey #8: Size-resolved CCN data.
13. APWG survey #1: Size distributions covering a wider range of sizes.

14. APWG survey #4: Vertical profiles.
15. Bioaerosol measurements could be relevant to INP at some locations/times. Might need more focused process-level study.
16. APWG survey #7: Morphology and composition of single particles.
17. In my experience, it is difficult to understand measurement quality without talking to instrument mentors. This is not a scalable process.
18. Sampling issues: Impactors described in AOS paper and raw data, drying is approaching success, but not there yet. RH is defined in AOS paper.
19. Can gridded data sets be produced for use by modelers?
20. Should consider reverting to simpler impactor cycle. This was introduced based on concerns with perturbing scanned measurements (fRH, HTDMA).
21. Support for more ARM-led publications of aerosol measurements to demonstrate the vast range of in situ measurements with the known details from calibrations to intercomparisons to higher-level data epochs.
22. Can we learn more from NASA in terms of production of different levels of data products with different levels of QC and clearly communicating that and making it easy for users to find the right level of processed data?
23. Mentors and translators meeting is not enough. Need scientists and vendors as well.
24. Could ARM expands its long-term measurements? What would be required for that: more investment in technical staff (trained technicians rather than scientists) to set up/maintain those? Something else?
25. APWG survey #6: More info on IN.

Recommendation #3: Propose an ARM data product and instrument mentor yearly meeting to review current set of measurements and data products.

1. Need more people involved than just translators and mentors. DQO, product engineering lead, etc.
2. This is best recommendation of the workshop so far. We NEED to do this to get the data in the ADC in the shape that we keep asking for.
3. Strongly support.
4. I think this sounds good in theory but could be very difficult in practice. Mentors and translators are already pretty overwhelmed and this would be adding more work.
5. Mentors and translators are not enough: need experts, users, vendors, etc.
6. Make more use of DQO capabilities to provide continuous assessment of relevant instrument intercomparisons for QA/QC purposes (e.g., comparing integrated number concentrations from SMPS and CPC).
7. Should ARM do more outreach with the aerosol science community, for example, with presentation at AAAR and other relevant conferences/workshops that specifically highlight ARM capabilities in various ways?

Recommendation #4: Publish ARM-specific studies (currently reports) in peer-reviewed literature.

1. Calibration processes are documented in handbooks, but we likely need to better communicate the results of calibration.
2. We have gotten continuous input that the technical aspects of the measurement also need to be in the literature. Mentors need support for the time to get this done.
3. Asking for recommendations and prioritization of publications.
4. Sampling issues (unsaid) historical timeline of operational modes.
5. Instrument lifetime should be considered programmatically. Rather than exhaust ourselves on the new PSAP filters, we probably would have been better off looking at the new instruments a couple of years ago.
6. More publication on ARM data seems like a good idea, especially if they can be directly liked to published, QCd data sets with DOIs, that can be easily downloaded.
7. Modelers don't care about the details of the calibration procedure, but we do need an estimate of uncertainty. Even a crude estimate of uncertainty is better than no estimate.
8. I've heard that ARM scientists and engineers have trouble finding time to write high-quality publications (even though they want to) alongside their "day jobs". Is this an obstacle to more papers on ARM data?
9. Calibrations and uncertainties are OFTEN not known after the measurement. Maybe even a year or more.
10. Please don't be overly optimistic about data product status. Nice hearing work about calibration issues, etc. But that does not necessarily flow into a final data product that a user is really interested in.

Recommendation #5: Run seasonal IOPs at fixed locations with more complex ARM and guest measurements, to ensure long-term coverage of measurements, but without full-time collection to maximize scientific output in terms of data quality, publications, and outside engagement.

Are there any strengths to this strategy? 17 votes – 71% Yes, 29% Maybe

Strengths of Strategy:

1. Focus on high-quality data and engagement with PIs and effort.
2. Draws the attention of the larger community, can extend to be an aerosol modeling testbed.
3. Leverages already what ARM does for IOPs but make it a consistent IOP timeframe. Unlike now, where IOPs happen when a PI wants to come to the SGP.
4. Coordination of PIs, mentors, and team-based aerosol science with the potential for high-impact publications incorporating ARM and PI/guest measurements.
5. More focus on making sure the measurements are working as well as possible.
6. More types of measurements at the same time, even for a short period, is attractive for modelers (perhaps not climate modelers, but people may be more interested in process modeling).

7. Increased interest (mentors, operators, scientists). Could improve measurement quality during period, but unclear how much. I see it both ways.
8. Fixed IOPs could result in an "enhancement" by motivating other PIs to conduct their respective IOPs at the same time. Perhaps leading to the whole being larger than the sum of its parts.
9. Strengths – depend on two important questions 1. Will this strategy improve the quality of our measurements at SGP? 2. Does this impact the usefulness of ARM long-term data sets?

Weaknesses of Strategy:

1. There is danger in shutting down and restarting some instrumentation. Things break less often just keeping them up.
2. ARM does host IOPs year round, so it sounds like this is just an ARM-driven process to try and communicate between PIs and set an optional "intensive" period. I don't think we would want to shut off the rest of the year to individual PIs, though.
3. "Campaign fatigue" by the instrument mentors.
4. Can ARM handle this in terms of $$$ and time? Do benefits outweigh any reprioritization efforts that may be needed?
5. Can't make this relevant to everyone for each IOP;-need to be willing to let each have its focus and if it's useful to some models and not others let it be (doesn't have to be a weakness).
6. Instruments that are run only in the proposed IOP strategy and not as core instruments (as they currently are) means funding for maintaining them will only be during IOPs. This could be problematic for mentors who rely on this funding.
7. The field campaign paradigm has been a success. Is this going to change the drivers of field campaign/IOP proposals from science to aligning with a random infrastructure-driven focus?
8. Is the prioritization of process-related studies short-sighted? Is the cost of losing the long-term more comprehensive measurements and seasonality too much?
9. If we take the operation of an instrument from 52 weeks/year to 2 weeks, the funding for the mentors should adjust accordingly. With some exception of prep time, calibration, and analysis. I think this needs to be thought about carefully.
10. Analytically, 24-h/12-month operation has advantages. A modification might be to operate 24/12 but have 'IOP' mode 4x/yr. Mentors would analyze (to high level) the 'IOP' periods. This has been done for the SP2 for the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) campaign.

Recommendations #6, #7, and #8:

Build infrastructure around AMF3 (roving medium-term site) to enable new sampling strategies, such as vertical profiling, distributed networks, and significant guest measurement accommodations.

1. #6 − Good idea, but need to understand the scope to determine resources needed.
2. #6 – I've felt the site selection for SE U.S. location for AMF3 should be a facility (Tennessee Valley Authority?, Georgia Institute of Technology?) that can provide supplemental measurements, thus leveraging the ARM contribution.

3. #6 – I agree with this.
4. #6 – Seems it would be very useful to the community; its's easy to do at SGP but we'd like to have this kind of model box-filling capabilities in other regimes.
5. #6 – Strongly support.

Propose allowing Level 1 and 2 ARM proposals to accept and fund instrument deployment and measurement data QA/QC projects that (are coherently proposed and) represent measurements/instrument capabilities that fill ARM-specific scientific knowledge gaps.

1. On 7, what would ARM not fund in order to fund guest IOPs? Reduce instruments? Mentor funding? Produce development?
2. On #6 #7, Does lack of PI funding provide a barrier for significant work? Regardless, I found the refusal to provide PI support to be …
3. #7 DOE has to make this change. It will apply to all field campaigns and not aerosols only. May lower $$ to other campaigns.
4. #7 Why not allow guest instrumentation proposal to also request funds for travel/lodging? Can we use existing protocols to accomplish this?
5. #7 – Sounds good but perhaps one could start slowly and set aside a smaller amount of funds initially to check and see if this might work well.
6. #7 Refusal to pay for PI support seemed somewhat arbitrary.
7. #7 – Suggest that this be incorporated into the DOE Small Business Innovation Research (SBIR) call rather than the $ coming out of ARM.

Continue to become more involved in the wider aerosol community!

1. #8 Certainly; however. we need some evaluation of IMPROVE data with ARM measurements (and other data as appropriate).
2. #8 – Agreed.
3. ARM could join Skynet or EuroRad, but would need to process data ourselves unlike AERONET.
4. Strongly agree with all three recommendations.
5. #8 – Yes, I do think community engagement is important/essential.
6. #8: Presentations at relevant conferences and workshops to advertise opportunities and capabilities (e.g., AAAR, American Geophysical Union, European Geophysical Union, International Global Atmospheric Chemistry project).
7. #8 – Continue these efforts.

Other recommendations:

1. For highly processed data products, include explicit uncertainty quantification directly with the data. Ideally every data point should have a (min, max) error bar associated with it.

2. More studies that sample the activation state of aerosol (in cloud droplets and ice crystals inside real clouds as a function of aerosol size, composition would be useful for understanding/evaluating in-cloud scavenging).
3. Particles larger than 1-2 microns are important for INPs, also potentially as giant CCN. When they are cut off by inlets, we may miss out on interesting, forward-looking science questions.

Appendix C

Status of AOS Datastreams

	Datastreams		
Instrument	a-level	b-level	c-level
ACSM	aosacsm.a1	Planned in FY20	CDCE VAP Planned in FY20/21
AETH	aosaeth1spot.a1 aosaeth2spot.a1	aosaeth*spot.b1 (in PCM)	
APS	aosaps.a1 aosapstof.a0 aosapssidescatter.a0	Planned in FY20	
CAPS	aoscaps.a1	aoscaps.b1	
CAPS3W	aoscaps3w.a1	aoscaps3w.b1	
CLAP	aosclap3w.a1	aosclap3w.b1 aosclap3w1m.b1	aopclap1flynn1m.c1 aopclap1flynn1m.s1
CCN100	aosccn100.a1	aosccn1colavg.1 aosccn1col.b1 aosccn1colspectra.b1	Kappa VAP planned FY20/21 CCN Profile planned FY20/21
CCN200	aosccn200.a1	aosccn2colaavg.b1 aosccn2cola.b1 aosccn2colaspectra.b1 aosccn2colb.b1	Kappa VAP planned FY20/21 CCN Profile planned FY20/21
CO	aosco.a1	Planned FY21	
CPCF	aoscpcf.a1	aoscpcf.b1 aoscpcf1m.b1	
CPCUF	aoscpcuf.a1	aoscpcuf.b1 aoscpcuf1m.b1	
CPCU	aoscpcu.a1	aoscpcu.b1 aoscpcu1m.b1	
HTDMA	aoshtdma.a1		
IMPACTOR	aosimpactor.a1	aosimpactor.b1	
AOSMET	aosmet.a1		
NANOSMPS	aosnanosmps.a1	Planned in FY20	

	Datastreams		
Instrument	**a-level**	**b-level**	**c-level**
NEPHDRY	aosnephdry.a1	aosnephdry.b1 aosnephdry1m.b1	
NEPHWET	aosnephwet.a1	aosnephwet.b1 aosnephwet1m.b1	
OZONE	aoso3.a1	Planned FY20	
PSAP3W	aospsap3w.a1	aospsap3w.b1 aospsap3w1s.b1 aospsap3w1m.b1	aoppsap1flynn1m.c1 aoppsap1flynn1h.c1
SMPS	aossmps.a1	Planned in FY20	
SO2	aosso2.a1	Planned in FY21	
SP2	aossp2aux.a0		aossp2rbc1m.c1
TAP	aostap.a0	aostap.b1	
UHSAS	aosuhsas.a1	Planned in FY20	

In order to continue to better serve the scientific community and based on recommendations by the AMSG, ARM continues to improve its processing efforts. New data products that will be operational in FY20 include:

- Quadrupole − ACSM b1-level data for SGP and ENA sites. This processing reports the mass concentration of organics, nitrate, sulfate, ammonium, and chloride in ambient aerosol as measured by the ACSM (assuming CE =1) along with the appropriate QA/QC checks. The mass concentration is also summed and converted to a total volume concentration for comparison to integrated size distribution measurements.
- APS, SMPS, nano-SMPS, UHSAS b1-level data. This processing will report size distributions from these instruments in common dN/dlogDp units, provides integrated volume, surface area, and number concentrations, reports QA/QC, and any additional instrument-specific data.
- Ozone b1-level data for Oliktok Point, SGP, and ENA. This processing applies laboratory calibrations, applies a baseline correction to the ozone concentration measurements, and provides QA/QC.

VAPs currently in development include:

- Quadrupole ACSM c1-level VAP. This VAP will apply the composition-dependent collection efficiency (CDCE) correction (Middlebrook et al. 2012) to the quadrupole ACSM data.
- CCN Profile VAP. This VAP combines lidar data and ground-based CCN measurements to estimate the vertical profile of CCN.
- CCN kappa VAP. This VAP combines CCN data and size distribution measurements to estimate the hygroscopicity parameter (kappa) for aerosol.

- AOD VAPS. The QC-AOD best estimate VAP compares AOD from co-located instruments at the SGP site and recommends the best value for use. Data will be released for SGP covering 1994-2018. We expect to release the data for Macquarie Island and the ENA site.

Data products planned for FY21 include:

- Quadrupole ACSM – b2-level data for the SGP site. This data is mentor-processed ACSM data assuming CE=1. It will have additional mentor-applied corrections and QC not found in the b1-level files.
- ToF-ACSM – b1- and c1-level data for the time-of-flight ACSM. These datastreams contain the same information as for the quadrupole ACSM.
- B1-level processing for CO and SO_2 instruments. This processing will apply calibrations and QA/QC. (from Art Sedlacek: I am bit confused here. We've talked about the ACSM, CCN, size distribution extensively in this document and now we start calling out VAPs for mature measurements like CO, SO_2, and O_3 (above). Why just these three mature instruments? Seems to me, depending upon the instrument, something similar can be applied to every aerosol measurement. If considered important, then solicit this level of information for each instrument but put the major list in the appendix and only list those instruments that have been the center of discussion.)
- A VAP reporting merged size distributions for SGP will be started, though unlikely to be completed. This VAP will merge size distribution measurements from instruments that span distinct size ranges (e.g., SMPS and aerodynamic particle sizer [APS]).

Appendix D

Table of Recommendations from the 2019 AMSG Workshop

Data Quality	
Short-term	Consider siting implications for local-source contamination; develop data quality flags for influence from local sources at each ARM site.
	Develop and publish aerosol instrument calibration and sampling protocols; engage directly with WCCAP and follow international procedures where appropriate.
	Use closure studies to ensure internal consistency among measurements of aerosol properties.
	Invest in relationships with instrument vendors that include mentors, translators, and key users.
	Perform AOS inlet characterization for large particles.
	Evaluate the current inlet drying method.
	Develop methodology to track instrument issues in a more quantitative way.
Long-term	Invest in ARM internal instrument intercomparisons.

Measurements and Data Products	
Short-term	Composition: Complete processing system for ACSM.
	Humidification/size: Implement HTDMA ambient (“SMPS mode”) scan where possible.
	CCN/IN: Implement CCN kappa product.
	CCN/IN: Implement flow scanning for CCN.
	CCN/IN: Implement multi-instrument CCN profile VAP, starting with the HI-SCALE period at SGP.
	Absorption: Develop a path forward for replacement of discontinued PSAP.
	Remote Sensing: Provide CIP VAP for all ARM MFRSR data.
	Remote Sensing: Develop a plan for providing or improving extinction profiles from multiple lidars.
	Remote Sensing: Develop plan for $3\beta2\alpha$ lidar retrievals or multi-wavelength lidar + passive retrievals.

Measurements and Data Products	
Long-term	Composition: Develop size-resolved composition measurements.
	Humidification: Assess implementation of additional humidigraphs.
	Size: Implement a unified/merged size distribution datastream reconciling different methods.
	CCN/IN: Increase frequency of INP measurements.
	Vertical Profiling: Improve data logging for TBS (on-board) to increase ease of data use (RS/VP).
	General: Expand ARM's interface with external networks (e.g., AERONET, IMPROVE, EBAS, NOAA Federated Aerosol Network).

Sampling Strategies	
Long-term	Develop 3-tier measurement strategy involving long-term observations, intensive periods, and guest instruments with consideration of needs for model improvement: o Determine the long-term versus intensive instrument list (may vary by site) o Consider seasonal IOPs at fixed locations with a more comprehensive suite of measurements (more complex ARM and guest instruments). Focus on aerosol sampling during field campaigns (as opposed to long-term measurements).
	Develop new measurement strategies with consideration of needs for model improvement: o Vertical profiling o Distributed networks o Integrating remote-sensing and in situ measurements including vertical profiling. Expand guest instrument support.
	Implement process to engage PIs regarding configuration of complex instruments.
	Consider routine (bi-weekly?) flights between SGP and SE U.S. AMF3 site.

Data Useability and Usership	
Short-term	Expand the number and type of aerosol modeling users. Provide modeler-specific data processing (bundles) with information characterizing data products.
	Improve web interface for information about: o AOS complement at each site, including timelines of instrument up-time o Where we are and are not following international calibration protocols.

	Tracked versions (living document) of calibration whitepaper.
	Improve metadata for aerosol instruments and measurements.
	Use metadata to improve aerosol recommended datastreams and their accessibility/visibility.
	Identify targets for characterizing measurement uncertainties.
	Implement joint ARM aerosol translator-mentor annual meeting.
	Facilitate measurement science and instrument peer-reviewed publications (in addition to ARM reports) by mentors describing ARM capabilities.
	Comparison between aerosol property retrievals from multiple passive and active sensors.
Long-term	Expand ARM presence (data use) in aerosol process community: o Expand presence at AAAR meetings o Share ARM data with other groups, their archives, and assessment reports/publications. Participate in national and international measurement intercomparisons.
	Continue ASR data products call?
	Propose allowing Level 1 and 2 ARM proposals to accept and fund instrument deployment and measurement data QA/QC projects that (are coherently proposed and) represent measurements/instrument capabilities that fill ARM-specific scientific knowledge gaps.

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