U.S. DEPARTMENT OF ENERGY | Office of Science

DRAFT

Atmospheric Radiation Measurement (ARM) User Facility Decadal Vision – 2020 (Draft)

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ARM

DISCLAIMER

Acronyms and Abbreviations

3D	three-dimensional
ACE	ARM Computing Environment
ACSM	aerosol chemical speciation monitor
ACT	Atmospheric data Community Toolkit
ADI	ARM Data Integrator
ADW	ARM Data Workbench
AI	artificial intelligence
AMSG	Aerosol Measurements and Science Group
ARM	Atmospheric Radiation Measurement
BER	Biological and Environmental Research
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CPMSG	Clouds and Precipitation Measurements and Science Group
DOE	U.S. Department of Energy
E3SM	Energy Exascale Earth System Model
EESSD	Earth and Environmental Systems Sciences Division
EMSL	Environmental Molecular Sciences Laboratory
ENA	Eastern North Atlantic
ESM	earth system model(s)
FAA	Federal Aviation Administration
G-1	Gulfstream-159
HTDMA	humidified tandem differential mobility analyzer
LASSO	LES ARM Symbiotic Simulation and Observation
LES	large-eddy simulation
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
OSSE	Observing System Simulation Experiment(s)
OSTI	Office of Science and Technical Information
Py-ART	Python-ARM Radar Toolkit
SCM	single-column models(s)
SCREAM	Simple Cloud-Resolving E3SM Atmosphere Model
SGP	Southern Great Plains
TBS	tethered balloon system(s)
UAS	unmanned aerial system(s)

Table of Contents

Introduction

The Atmospheric Radiation Measurement (ARM) user facility was established in 1989 by the U.S Department of Energy (DOE) Biological and Environmental Research (BER) program to provide an observational basis for studying the Earth's climate. ARM began collecting observations in 1992 and was designated a user facility in 2003. The facility includes a network of extensively instrumented long-term fixed-location observatories and mobile facilities. The ARM facility also includes an aerial component to augment these ground-based measurements. Because of the diversity of in situ and remotely obtained observations, ARM's data management infrastructure is designed to collect, process, and deliver data to the research community (U.S. Department of Energy 1990, Stokes and Schwartz 1994, Ackerman and Stokes 2003, Mather and Voyles 2013, Turner and Ellingson 2017).

The mission of the ARM facility is:

> *(to provide) the atmospheric research community with strategically located in situ and remote-sensing observatories designed to improve the understanding and representation, in atmospheric, climate, and earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth's surface.*

Over the past decade the ARM facility has undergone significant changes, including the addition of new measurement capabilities (Mather and Voyles 2013); the creation of a new mobile facility at Oliktok, Alaska; a new fixed-location observatory in the Eastern North Atlantic (ENA); the cessation of operations in the Tropical Western Pacific after 18 years (Mather 2015); development of new aerial measurement capabilities (Schmid et al. 2014, de Boer et al. 2018); the implementation of high-performance computing capabilities; and the development of a high-resolution modeling framework to better link ARM observations with cloud-resolving, regional, and large-scale earth system models (Gustafson et al. 2020).

The ARM facility currently comprises three mobile facilities and three fixed-location observatories. In addition to ENA, the other two fixed-location observatories are the Southern Great Plains (SGP), which has been operating in Oklahoma since 1992, and the North Slope of Alaska (NSA), which has been operating since 1998. The mobile facility deployment to Oliktok was planned as an intermediate-length deployment of approximately five to seven years. The remaining two mobile facilities are deployed for shorter-term projects of the order six months to several years.

While the ARM mission will continue unchanged into the future, the vision and supporting activities require updating, in order to respond to evolving scientific challenges provided by the research community, new technological and operational opportunities identified by ARM management, and evolving strategic priorities within the DOE Earth and

Environmental Systems Sciences Division (EESSD). The purpose of this document is to describe the updated vision in order to address increasingly complex science challenges related to ARM's mission over the next five to ten years.

The updated ARM Decadal Vision

The DOE Earth and Environmental Systems Sciences Division has a vision to advance the predictability of the earth system, where science programs and user facilities collaborate in order to address the most difficult research challenges facing the scientific community. EESSD is also committed to providing the community scientific and technical capabilities in three areas, i.e., involving the atmospheric sciences; environmental system sciences; and earth and environmental system modeling. The ARM facility has been identified as the most important DOE investment to sustain the atmospheric sciences, i.e., as a means to realize the vision of EESSD. Over the next decade, EESSD is likely to more fully exploit emerging opportunities to more rapidly advance the science, including, e.g., more advanced sensor and observing networks, data analytics involving machine learning, high-performance computing, and hybrid modeling (various combinations of Large-Eddy Simulation, cloud-resolving models, ultra-high-resolution earth system models, and data assimilation). EESSM is also encouraging strengthened coordination, collaboration, and/or partnering with other agencies as a means to advance the science more rapidly. As ARM moves into the next decade, its vision will evolve with more sophisticated scientific questions and emerging technological opportunities.

The updated vision for ARM is:

> *To provide the research community with the best array of field observations and supporting state-of-the-art data analytics to significantly improve the representation of challenging atmospheric processes in earth system models*.

The updated ARM Vision will be sustained by activities organized within four themes:

1. Provide comprehensive and impactful field measurements to support scientific advancement of atmospheric process understanding
2. Achieve the maximum scientific impact of ARM measurements through increased engagement with observational data by ARM staff, including the application of advanced data analytical techniques
3. Enable advanced data analytics and community use of complex ARM data sets through the advancement of computing infrastructure and data analysis
4. Accelerate and amplify the impact of ARM measurements on earth system models (ESM) by exploiting ARM and ESM frameworks to facilitate the application of ARM data to ESM development.

These themes follow a progression beginning with enhancing ARM measurement capabilities according to the needs of the science community. The second theme focuses on characterizing ARM measurements and extracting as much information as possible from these measurements through efforts related to data analytics. ARM data have expanded in diversity, complexity and volume over the past 28 years and that trend is expected to continue. The third theme focuses on data services and how ARM can continue to improve these services to facilitate the use of ARM data by the research community. Finally, the ultimate goal of the ARM facility is to support the improved representation of atmospheric processes in earth system models. To some extent, this will follow from improved understanding that occurs when the science community utilizes ARM data in process studies. However, the fourth theme explores ways in which ARM can engage more directly with the modeling community.

The activities described in the following sections associated with these four themes do not represent a work plan. Rather, this document provides a vision of the areas in which ARM can improve its effectiveness within each of the four themes. This vision will lead to the development of specific plans to bring new capabilities to the user community. Some of these activities are already in progress, but others are ideas for future development that reflect needs that have been expressed by the science community or represent facility development that supports these needs. We plan to organize our efforts in the coming years around these themes and pursue the activities described here. However, we will also continue to engage with the community and adjust priorities according to that input as discussed in Appendix B.

T1. Provide comprehensive and impactful field measurements to support scientific advancement of atmospheric process understanding

The core mission of the ARM facility continues to focus on the advancement in understanding of atmospheric processes; however, the capacity of the facility and the technical opportunities to provide measurements have evolved. ARM is an operational facility that provides continuous observations at its ground-based facilities, but at the same time, it is a research facility that always strives to provide the highest level of information possible at its observatories to maximize their science impact.

We plan to achieve this enhanced science impact by deploying observatories where they are most needed by the science community, by providing the most comprehensive and useful measurements possible, and by expanding the spatial footprint of ARM measurements. The activities outlined below would aid ARM in enhancing its impact in one or more of these areas.

T1.1 Establishment of an observatory in the southeast United States for a multi-year study convective clouds, aerosols, and land-atmosphere interactions

In 2018, DOE sponsored a workshop to explore regions for which the atmospheric science community would particularly benefit from the suites of measurements provided by ARM's mobile observatories (U.S. Department of Energy 2019). The discussions included consideration of areas that would benefit from multi-year deployments due to significant interannual variability or a focus on rare meteorological events. One of the highlighted regions was the southeastern United States and that region has been selected by DOE for deployment of the third Mobile Facility (currently in Oliktok, Alaska). Planning is already underway for this deployment and operations are planned to start possibly as early as 2023. This site is expected to provide valuable data to address a set of emerging science challenges. For example, this deployment will allow a focused study on the relative importance of local forcing on the development of convection, where boundary-layer dynamics and land-atmosphere interactions in a heterogenous landscape are expected to be particularly important. ARM will be exploring strategies such as ancillary facilities, aerial measurements, and networks from collaborating organizations to characterize this heterogeneity. This region is additionally known to be a significant source region for secondary organic aerosols so it will provide a valuable data set for studying aerosol processes and aerosol-cloud interactions.

The same 2018 mobile facility workshop identified other areas with continued measurement needs. These were high latitudes, mountainous and complex terrain, marine regions, and regions with organized deep convection. ARM will support a study in complex terrain through the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign beginning in 2021.

T1.2 Provide advanced aerial measurements to support process studies and validation of ground-based measurements

Aerial measurements provide spatial context for ARM ground-based measurements, they provide information, such as the chemical composition of aerosols aloft or the microphysical properties of cloud droplets, via in situ measurements that are not possible from remote sensors, and they provide important validation of measurements that enable the development of retrievals from ground-based remote sensors. ARM has a three-pronged approach to aerial measurements with piloted aircraft, unmanned aerial systems (UAS), and tethered balloon systems (TBS) that each have their unique capabilities. ARM is actively developing new capabilities in each of these areas including a new piloted platform.

A new piloted research aircraft will modernize and expand aerial measurement capabilities

ARM has obtained a Challenger 850 (CL850) regional jet in 2019 to replace the Gulfstream-159 (G-1) aircraft, which served the facility from 2010 through 2018. The CL850 is in the process of being modified for research operations and is expected to be ready for science flights in 2023. The modification process includes the addition of wing pylons and fuselage mounting points for deploying instruments as well as internal infrastructure to mount racks, distribute power, and provide connectivity throughout the aerial laboratory.

The CL850 will provide in situ measurements as the G-1 did for nearly a decade while expanding on the capabilities of the G-1 in terms of maximum altitude, payload capacity, and endurance. The final numbers for each of these areas will not be known until the completion of modifications; however, they will represent a significant enhancement in each case. As will be seen in the next section, plans are also underway to further expand the capabilities of the Challenger by pursuing new measurement capabilities.

Exploiting TBS to obtain observations of the planetary boundary layer over ARM observatories

ARM TBS capabilities have matured significantly since first deployed at Oliktok in 2015 and TBS are now being flown on an episodic basis at both Oliktok (de Boer et al. 2019) and the SGP. TBS have the ability to carry relatively large payloads up to an altitude of approximately one kilometer. ARM plans to expand its use of TBS to other ARM observatories, including mobile facilities, and expand its measurement capabilities.

A particularly important target for TBS is aerosol profiling. Aerosol profiles are very difficult to obtain via remote sensing alone. ARM has started to experiment with filter sampling for offline analysis in collaboration with the Environmental Molecular Sciences Laboratory (EMSL). This has the potential to provide significant information about particle composition. ARM will continue to explore opportunities for enhanced TBS measurement capabilities including aerosol, cloud microphysical, radiative, thermodynamic, and dynamic properties.

Developing UAS capabilities to provide in situ measurements over ARM observatories

UAS excel at being highly maneuverable and providing high-spatial-resolution samples with a small-to-moderate payload. ARM has experimented with small UAS but given the prevalence of these small systems is focusing on the development of mid-size systems capable of carrying in excess of 25 kg. These larger UAS have the potential to provide high-spatial-and-temporal-resolution measurements of aerosols, clouds, and the atmospheric state over ARM sites. These larger UAS are also significantly more complex to operate than small systems. This complexity and associated cost put these systems beyond the capacity of most research groups and make them a good capability for a user facility. ARM is currently developing a mid-size UAS with a payload capacity of approximately 45 kg and has integrated a miniaturized set of instruments into this platform. The goal for this UAS is to obtain in-cloud observations over ARM sites. Currently, in-cloud flying is not permitted by the Federal Aviation Administration (FAA) so we will explore strategies such as the implementation of detect-and-avoid technology to enable this work. In the interim, we will target measurements of aerosol in clear air as we continue to develop this UAS platform.

Exploring new measurement capabilities for ARM aerial platforms

In March 2020, a workshop was held to review measurement capabilities for piloted aircraft along with miniaturized instruments suitable for UAS and TBS platforms. This workshop provided extensive information about new or emerging instruments that could be used to further enhance the capabilities of the CL850, UAS, and TBS. Over the coming few years ARM will identify opportunities to enhance aerial measurement capabilities by matching high-priority science needs with emerging instrument technology.

T1.3 Pursue the implementation of new measurement capabilities and operation of existing instruments in new ways at ARM ground-based observatories

The ARM facility currently operates over 400 instruments at six ground-based observatories and 50 instruments for aerial platforms. These measurement capabilities address a broad range of science targets and represent the most comprehensive set of continuously operating atmospheric measurements in the world. Nevertheless, there are opportunities to address currently unmet measurement needs and to improve or augment existing measurements. Some of the greatest measurement challenges are encountered in aerosols, clouds, and precipitation and those measurements will be the main focus of this section; however, ARM will also continue to engage with the community to identify opportunities to improve measurements of a broad array of physical parameters including broadband and spectral radiative fluxes, unsaturated thermodynamic properties, atmospheric motion, and land-surface properties.

Provide comprehensive aerosol measurements

ARM has significantly expanded its aerosol measurements over the past decade; however, given the complexity of aerosol life cycles and aerosol properties, there remain gaps in the needed measurements. ARM has engaged with the aerosol science community to understand how to best address these measurement needs (McComiskey and Sisterson 2018) and has identified a two-pronged approach: First, through continued efforts to identify and focus on the most impactful set of measurements and second, through collaboration with the broader science community. Plans for collaboration will be discussed in the next section (T1.4) with the highest-priority gaps briefly outlined here.

- Size-distributions: Aerosol size distributions from a few nm up to ~30 μm are important for most aerosol applications. The full range is provided by a combination of instruments. ARM currently provides this full set of instruments at the SGP but will strive to provide complete distributions across observatories.

- Hygroscopicity: ARM operates several instruments such as the humidified tandem differential mobility analyzer (HTDMA) that provide information about aerosol hygroscopicity; however, these instruments are highly configurable and the information on aerosol growth is complex. Work is needed to provide measurements and data products that are readily applicable to a broad set of science issues.
- Composition: ARM's primary instrument for aerosol composition is the aerosol chemical speciation monitor (ACSM), which is useful in many applications but lacks the resolution to study detailed aerosol life cycle processes. ARM will seek to identify new instruments that enable sustainable measurements of in-field composition measurements while also pursuing offline measurements through collaborations (as mentioned in T1.2 with EMSL) and with the broader science community (T1.4).
- Optical absorption and ice nucleating properties: ARM has provided filter-based measurements of optical absorption for many years and is beginning to provide filter-based measurements of ice nucleating particles. These filter-based measurements have been valuable, but there are questions of filter impacts on the measurements, which also lack the time resolution of in-line measurements. ARM will engage with the science community to identify new measurement approaches in these areas.
- Aerosol profiles: Most ARM aerosol measurements are made in situ near the ground though aerosol properties vary with height above the surface. ARM is taking steps to measure aerosol from aerial platforms (T1.2) and is implementing a multi-wavelength lidar capability that is expected to represent a significant step forward for providing aerosol properties aloft (Müller et al. 2014).
- Arctic aerosols: At Utqiagvik, ARM and the National Oceanic and Atmospheric Administration (NOAA) have collaborated to operate a small set of aerosol physical and optical property measurements at the adjacent NOAA baseline observatory beginning in 1997 (McComiskey and Ferrare 2016). We plan to evaluate priorities for Utqiagvik and expect to augment aerosol measurements there to meet critical science needs as we evaluate priorities across all ARM locations.

These represent current aerosol measurement priorities of the science community. In the coming years, ARM will continue to engage with the community to develop strategies to advance these capabilities and to continue to assess the relative priorities among these items as well as those that are not captured here.

Provide advanced measurements of clouds, precipitation, and related parameters

ARM has a long history of providing measurements of cloud properties using instruments such as millimeter cloud radars and microwave radiometers and has invested effort in recent years to provide more advanced measurements of precipitation through instruments such as video disdrometers. These instruments have provided unique and valuable measurements in many locations around the world but as with aerosol properties, there remain measurement challenges that impede scientific progress. Here we identify some important measurement needs that have been identified over the past several years for clouds as well as for precipitation. ARM will pursue advancing measurement capabilities in these areas and will continue to engage the science community to identify measurement priorities and new technologies that improve the characterization of these and other cloud- and precipitation-related parameters.

- Cloud droplet number concentration: ARM has implemented data products that provide droplet number concentrations through in situ measurements as well as through remote-sensing retrievals; however, work is needed to improve the accuracy of remotely sensed values.
- Liquid water path in the presence of precipitation: There has been much work on providing high-quality liquid water path measurements, primarily using microwave radiometers. In recent years, this work has included improved measurements for low liquid water paths; however, providing this measurement in the presence of precipitation remains a significant challenge and calls for development of modified measurements that minimize the collection of water on the radiometer and possibly modified retrievals.
- Cloud droplet phase and ice properties: A great deal of progress has been made in this area using multi-frequency radars, radar spectra, and combinations of active and passive remote sensors but there remains significant work to do, particularly with regard to deriving detailed properties of ice.
- Frozen precipitation properties: ARM has recently deployed several instrument systems on the North Slope of Alaska that provide measurements of ice particle shape, snowfall rate, and snow depth, and auxiliary measurements that help distinguish falling snow from blowing snow. However, work is required to fully apply these measurements to obtaining a quantitative snowfall rate and spatial variability, especially near the coast, is an issue that is beginning to be explored.
- Vertical air motion: Measurements of vertical air motion are critical for studying cloud processes. A variety of instruments and techniques are being used to obtain vertical air motion in various domains (e.g., below cloud base and within clouds), but significant challenges remain, including measurement of vertical motion above clouds and developing an integrated view of vertical motion.
- Three-dimensional cloud and thermodynamic fields: Scanning radars and stereo photogrammetry are providing valuable information about three-dimensional cloud fields, but work is needed to improve the reliability of scanning cloud radars and make the best use of these complex measurements. Meanwhile, Raman lidars and spectral infrared radiometers are being used to obtain thermodynamic profiles that represent the cloud environment. Obtaining three-dimensional thermodynamic fields, however, will require developing new measurement strategies, possibly combining remote sensing and in situ aerial measurements.

Though not directly related to cloud fields, we will also call out here spatial characteristics of surface properties and surface energy fluxes. These surface characteristics represent both a response to cloud and precipitation processes and can provide an important feedback to cloud properties. In a similar way as three-dimensional cloud fields, surface properties represent a challenge due to their spatial heterogeneity. Here ARM will engage with the science community to identify effective and efficient strategies to observe spatial variation in surface properties that are important to atmospheric properties observed at ARM sites.

These topics all represent significant measurement challenges. In some cases, progress is being made through the development of advanced retrieval techniques. ARM will continue to work with the community to identify opportunities to apply effective and robust retrievals to make these derived parameters available to the science community. Many or all of these measurements may also benefit from new instrument capabilities that ARM will seek to identify as they emerge. As an example, ARM is currently working to implement adaptive scanning with a centimeter-wavelength radar. However, like most weather radars, the ARM C-band radar uses a mechanical positioner with a relatively slow scan speed, so it will be limited in its ability to track the evolution of a convective cell. Phased-array radars offer a solution to this problem. These radars scan the radar beam electronically, and therefore can scan much faster than a mechanical system. ARM will track their evolution and look for opportunities to implement a phased-array radar for convective studies. Similarly, ARM will engage with the science community to explore opportunities to advance each of the measurement challenges identified here.

Maintaining a sustainable measurement network

It is important to acknowledge that the addition of new measurement capabilities requires resources, for the initial deployment, data product development, and ongoing operation and data processing. There is a perpetual demand for new measurement capabilities and developing technologies periodically provide opportunities to fill gaps. Therefore, when adding new instruments to the ARM network it is important to make space for the new capabilities by removing, or scaling back, facility elements to maintain a high level of support for remaining instruments and datastreams. ARM has developed an objective process for reviewing capabilities by examining their alignment with the ARM mission weighed against quantitative metrics, such as science impact through publications and citations, cost of operation and maintenance, and instrument uptime. We will use this process to help maintain a sustainable measurement network. We will also explore other creative solutions to effectively manage resources such as the proposed use of intensive periods discussed in the next section and increased use of automation (T2.3).

T1.4. Coordinated use of intensive operation periods to maximize the potential of complex ARM instruments and guest instruments

Complex instruments such as scanning radars and certain aerosol instruments take significantly higher levels of maintenance than most ARM instruments and may require extended offline periods for maintenance and characterization. This is challenging in terms of managing resources and unless a strategic operations plan is developed and followed, a key instrument may be offline at particularly inopportune times. Meanwhile, users of ARM aerosol measurements have noted that aerosol process studies are most effective when ARM measurements are combined with guest instruments.

Recent workshops led by two ARM user groups, the Aerosol Measurements and Science Group (AMSG) and the Clouds and Precipitation Measurements and Science Group (CPMSG), have noted that both of these issues can be addressed by focusing operation of complex instruments around intensive operational periods. The strategy would be to define several periods per year at one or more ARM observatories that would represent intensive operational periods. These periods would be driven by science community needs and would be advertised in advance with an invitation for the community to propose guest instrument deployments. This coordination would significantly increase the chances of obtaining a critical mass of observations for various science applications and would generally increase the visibility of the event to the community as multiple investigators engaged. Additionally, ARM would organize its characterization and implementation of relevant instruments to optimize performance during the intensive periods and to configure instruments to best serve the goals of that period as identified by the science community. Through this coordination, the value of measurements during the intensive period would be significantly enhanced relative to normal operations.

T1.5. Deployment of multiple facilities or observatories to support multi-scale analysis

ARM observatories provide extensive measurements at a single geographical point but typically do not provide significant information about the surrounding region (the SGP extended facility network and measurements provided by scanning radars and the aerial facility being notable exceptions). Process studies, such as the evolution of deep convection, sometimes depend on regional measurements so there would be significant value in expanding efforts to modify sampling strategies to obtain additional spatial information. Here we propose that ARM consider creative ways to deploy facility components to provide this spatial information when it is critical for advancing the core science questions associated with a deployment.

Satellite measurements and networks from other organizations are sometimes used to augment ARM measurements and they should be used on a more regular basis and in a more coordinated way when developing a spatial sampling strategy. Aerial measurements will also continue to be used to provide spatial information on an episodic basis. But we will also consider the strategic deployment of ground-based measurements. For example, ARM could redeploy the SGP boundary-layer profiling stations to observe spatial variability in boundary-layer structure. These were originally designed to be portable and could be relocated to other sites around the SGP or another ARM observatory. Alternately, ARM could design compact and modular observing systems that would enable spatial sampling of small sets of parameters, such as surface fluxes, in conjunction with mobile facilities. One could even imagine the deployment of two or more ARM observatories in tandem to measure the evolution of atmospheric properties along a natural gradient (U.S. Department of Energy 2014, Stacey and Hungate 2018). To conduct such a multi-observatory experiment, ARM could have a special facility call that invited proposals to use multiple facilities.

T2. Achieve the maximum scientific impact of ARM measurements through engagement with data including the application of advanced data analytical techniques

There have been frequent discussions with the user community and among ARM staff in recent years that emerging analytical tools, such as those readily available machine learning libraries, have the potential to amplify the value of ARM measurements. Application of machine learning, for example, has the potential to help identify data quality issues, estimate measurement uncertainties, and reveal complex relationships among parameters. However these techniques require that the underlying data be well characterized.

In the previous section we explored potential new measurement opportunities. In this section we consider how additional benefit can be extracted from existing measurements through a focus on data analysis. We begin with discussion of the fundamental work that needs to be done with ARM data by ARM staff and progress to potential applications of advanced data analytics.

T2.1. Improve transparency of data characterization activities and empower ARM staff to engage with data to enhance measurement characterization

A typical ARM observatory deployment provides on the order of 50 different measurements ranging from basic meteorological parameters and the surface radiation budget to profiles signals from active remote-sensing instruments that provide information about aerosol and hydrometeors. For an investigator to derive useful information from a measurement, or combinations of measurements, they need to have a good understanding of the characteristics of that measurement. ARM has processes in place to manage the operation of each instrument including calibration procedures and the assessment of data quality; however, more could be done to communicate the details of these processes and information about calibrations is not generally accessible to users. ARM will undertake an evaluation of how to improve the transparency of these processes and the related information and engage with the science community to ensure that they are being applied in the most effective manner.

ARM is also exploring how it could devote more resources to the analysis of measurements and the subsequent communication of the results from these analyses to enhance the application of these data by users. These analyses should include: statistical characterization of measurement distributions, identification of measurement anomalies, assessment of measurement uncertainties, characterization of effective spatial and temporal resolution, and quantification of parametric relationships among measurements. Additionally, ARM should provide software tools to enable this work by the user community to leverage its broader analytical capacity.

T2.2. Development of closure studies and other internal analyses to create internally consistent data sets for measurement characterization and application to process studies

In addition to characterizing individual measurements, it is valuable to analyze groups of related measurements. For example, in closure studies, groups of measured parameters are used to predict another measured parameter. The accuracy of the prediction provides information about the uncertainty in the measurements or understanding of the expected relationship.

As mentioned in the previous section on new measurements, ARM has begun to fly small aerosol sensors on tethered balloons and is working toward similar measurements on UAS. From these measurements, one could calculate the vertical profile of aerosol properties such as optical extinction. ARM also operates lidars at its observatories that provide this same quantity. Providing these in situ measurements on a frequent basis in addition to the remote sensors would enable a closure study to be conducted on the column aerosol optical properties. ARM could organize and quality-control all of these measurements into an integrated data set to support aerosol process studies. Other examples of closure studies include comparing predicted broadband or spectral radiative fluxes or radiances derived from observed atmospheric properties with radiation measurements at the surface, or integrating water content to obtain total water path.

In another example of multi-variable analysis, groups of measurements can be used to characterize the state of the environment to define an atmospheric regime. The parameters used to define the regime could be drawn exclusively from ARM measurements or they could be taken in part from external sources, such as satellite observations or even model reanalysis. Once identified, data from a particular regime will be tagged to help researchers find data that meet certain criteria (such as conditions conducive for a certain phenomenon of interest) but such data could also be used to refine analysis of measurement behavior. In the previous section, an argument was made for characterization of parameters. If a parameter is constrained by a particular regime, then the distribution of a parameter may take a form particular to that regime. This would aid the identification of outliers and advance the understanding of measurement uncertainty.

T2.3. Apply advanced data analytical techniques to enable automated quality assessment, the identification of parametric relationships, and enhanced instrument operations

Carrying out a closure study, as described in the previous section, results in a data set that is internally self-consistent, or the degree of inconsistency becomes much better understood. With such a multivariable data set, it becomes possible to move ahead with more advanced analytic tools. State-of-the-art machine learning and data analytics algorithms and high-performance computing offer opportunities to realize the potential for new understanding in atmospheric processes and phenomena observed during the long history of ARM observations.

We propose to develop and apply platforms to support scalable parallel machine learning algorithms for data quality analysis of ARM data to gain new insights into processes captured by not one, but an array, of co-located sensors/instruments in tandem. These applications have the potential to aid in assessing data quality by helping to identify data outliers and to support the development of new value-added products or provide a constraint for model parameterizations by identifying relationships among parameters. Infrastructure and tools developed would be targeted towards improving the operational efficiency of ARM data quality analysis and integrated with existing data quality operations.

Besides extracting information from ARM measurements, machine learning and similar applications can help with field operations. We plan to explore the use of edge computing in ARM instrument fields. This has several potential applications. By applying quality assessment algorithms at the instrument, it may be possible to identify instrument problems in near-real time. It may also be possible to identify alternate instrument operational states. A relatively simple example would be making the decision to save Doppler spectra from a radar or lidar. Doppler spectra contain important information, but they only contain useful information under certain conditions and they can dominate data storage requirements. Therefore, an automated mechanism to decide accurately when to save spectra would be valuable. Another example is providing real-time adjustment to instrument scanning strategies.

Adaptively operating instruments has emerged as an effective technique for focusing measurements on specific atmospheric conditions. In adaptive mode, the physical operation of an instrument is modified in response to the physical conditions it is measuring. ARM currently has implemented an algorithm for switching operating modes for the radar wind profiler between wind sampling and precipitation modes using a set of specific pre-selected criteria. Likewise, precipitation radar scans have been adapted in real time to track storms as they advect through the observation domain using human decision-making. Artificial intelligence (AI) provides a framework for training automated algorithms that could adapt to the operating conditions for various instruments either in isolated ways or as an integrated system that adapts together based on a specific set of science questions. Examples might include tracking convective cells and the environmental conditions leading up to and during storm events using scanning radar and lidar, or modifying sampling intervals when specific aerosol conditions occur.

T3. Enable advanced data analytics and community use of complex ARM data sets through the advancement of computing infrastructure and data analysis tools

The ARM Data Center currently holds over 2 petabytes of data from over 11,000 data sets and these numbers are steadily increasing. This increase results from increasingly complex instrumentation, continued development of advanced data products, and the implementation of high-resolution model simulations. To advance the data analysis applications discussed in the previous section and the usability of ARM data by the science community, it is important to continue to develop ARM computing platforms and tools.

In this section we discuss plans to expand computing infrastructure to support growing volume and to expand processing applications and develop tools and software practices that would facilitate user engagement with ARM data.

T3.1 Develop a flexible computing environment that makes use of internal high-performance computing infrastructure and data analysis tools

The ARM Data Center constantly assesses computational requirements associated with the application of ARM data and continues to develop mechanisms such as the implementation of computational clusters to meet those needs.

ARM Computing Environment (ACE) strives to address the computational needs of the ARM infrastructure and science communities by providing a range of computing hardware and software solutions. Operational and research computing across ARM ranges from processing of high-volume ARM data sets to high-resolution modeling as well as emerging big-data science and machine learning/AI. To support heterogeneous and increasing computational requirements, we plan to expand ACE's hybrid computing environment to include an appropriate mix of high-performance computing and cloud computing resources for seamless access and an improved computing experience to adaptively meet the wide range of computing, memory, and storage needs of ARM.

T3.2 Developing software tools to enable data access and analysis

With the expansion of ARM data volume for data sets from instruments such as scanning radars or ARM model simulations, we have received requests from the science community to enable local computing at the ARM Data Center. We propose to develop an ARM Data Workbench (ADW) that will be a revolutionary way to interact with the vast amount of data ARM has to offer. This workbench will give users the tools to find, visualize, and even create their own mash-up data products. Using technologies like Apache Cassandra and Spark, we have access to all the data for select datastreams readily available. This gives the ability to filter data and apply equations to make a unique data product for the community's needs.

The workbench would be an extension to the current Data Discovery and would provide the tools for users to select data by conditional statements or date range. The workbench would provide a platform for the users to bring in any open-source, equation-based calculations and run the analysis on the selected data intervals.

It is clear that tools are needed to facilitate access to ARM data sets and the capabilities described for the workbench represent ideas for what would be valuable to the science community; however, before embarking on the development of such a system, we would engage with focus groups to assess interest and determine functionality that would have the greatest impact.

T3.3 Enabling open-source software practices to support sharing of code among ARM staff and with the ARM user community

ARM uses a wide variety of software tools. In many cases, tools developed for one purpose may be adaptable for other applications. There is an increasing need for users to develop code in an open manner. ARM has implemented a new strategy to share and enable users to contribute open-source code. ARM has restructured its presence on Github, resulting in three Github organizations. The ARM-DOE organization will only host ARM-supported repositories, such as the Python-ARM Radar Toolkit (Py-ART), the ARM Data Integrator (ADI), and the Atmospheric data Community Toolkit (ACT). One organization will be dedicated to hosting software from the user community and another will be a development area for ARM infrastructure and data users to try out new ideas. ARM will use metadata from the DOE Office of Science and Technical Information (OSTI) to provide users information about the codes through our Data Discovery interface.

As ARM works towards more community-driven open-source software and tools like Py-ART and ACT, new opportunities will arise to advance the processing capabilities and the way in which data is provided to end users. The ability to easily integrate codes from these open-source tools could potentially allow for the easy integration of these codes into processing on demand in which users could easily specify additional processing they want to be applied to the data.

T4. Amplify the impact of ARM measurements on earth system models (ESM) by exploiting ARM and ESM frameworks to facilitate the application of ARM data to ESM development

The ultimate purpose for the ARM facility is to support the improvement of models that extend from cloud-resolving on regional scales to large-scale earth system models such as E3SM. Over the years, ARM data have been used to improve the representation of radiation, aerosols, and cloud processes in climate models through direct application of ARM data and through intermediate process studies (Randall et al. 2016). These same modes of engagement, as well as supporting model development indirectly through support of process-level understanding, continue to be important. Nevertheless, we have taken steps to be more proactive in pursuing these opportunities to impact models and plan to continue to advance these strategies in the coming years. These strategies include implementing a high-resolution modeling framework to bridge scales and creating direct connections to the modeling community through diagnostics based on ARM data and supporting single-column model cases over ARM sites.

T4.1. Apply the LASSO observation-model framework to new meteorological regimes and generalize for implementation over any ARM observatory

Building on the long-used method of using high-resolution, limited-area models to link ARM observations with large-scale models, ARM recently developed and implemented the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) workflow (Gustafson et al. 2020). LASSO includes LES simulations over an ARM site, forcing data sets used to initiate the simulations, model output bundled with ARM observations, and automated model diagnostics based on ARM observations. Over the past five years, LASSO has been applied at the SGP site with a focus on summer shallow convection. Application of LASSO has led to an improvement in related ARM measurements (e.g., for liquid water path and boundary-layer turbulence), a flurry of research related to boundary-layer processes at the SGP, and a remarkable library of LES simulations that is being used for parameterization development and studies of shallow cumulus properties.

ARM is now turning the application of LASSO to the study of deep convection with an initial focus on the recent mobile facility deployment to Argentina for the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) campaign. Deep convection was observed on 80 separate days during CACTI. The addition of LASSO simulations to the rich CACTI data set will support analysis of deep convection dynamics and its relationship to observed cloud properties.

While work is moving ahead with the deep convection case, there is also strong community interest in additional meteorological regimes (Gustafson et al. 2019), in particular marine stratocumulus, arctic clouds, and stable boundary layers. We expect that each of these scenarios will be implemented over time and that additional cases will be identified as ARM measurements are obtained in new environments. The ultimate goal is to develop LASSO into a sufficiently flexible framework to be implemented over virtually any ARM observatory where it is determined that the simulations would provide significant scientific benefit.

T4.2 Organize ARM measurements around virtual field campaigns to facilitate access to broad sets of related data and support observation-model collaborative projects

The data tagging mentioned in association with meteorological regimes in section T2.2 is planned to be part of a larger effort to classify the data with respect to topics such as data quality or meteorological conditions. Another envisioned application of metadata tagging is to link together a set of data products intended for use toward a common project. Such an array of data sets, tagged for specific time periods, would constitute a virtual field campaign. Organizing data around virtual field campaigns would provide a valuable technique to facilitate the use of ARM data by modeling groups or other communities that are less familiar with ARM data. Like a real field campaign, a virtual field campaign would focus on a particular set of science goals at a particular location, but unlike an actual field campaign, it could draw on routine measurements.

A common historic practice for linking modeling teams with observations has been to define a focused project involving an observation case or set of cases. These activities typically involve a significant amount of up-front work to organize the project data sets. Virtual field campaigns that are organized through metadata tags would lower the barrier to setting up a modeling project based around measurements (U.S. Department of Energy 2016).

T4.3 Exploit model configurations and tools such as single-column models, regionally refined mesh, and instrument simulators to effectively link ARM data to ESMs

One of the motivations for LASSO is to provide a link between high-resolution ARM measurements and global-scale models. However, ARM data have also been used to evaluate large-scale models directly. One mechanism that has been used to do this is application of single-column models (SCM) in which a single column from a global-scale model is run over an ARM site using the same type of dynamic forcing that is used to run a high-resolution, limited-area model like the one used in LASSO. Many SCM cases have already been developed around ARM sites. We plan to continue working with the Energy Exascale Earth System Model (E3SM) community to identify cases, particularly those associated with LASSO simulations or virtual campaigns, which have been identified as period of particular scientific interest. We believe that building on this case library could lead to a powerful strategy for using ARM data for model development. Given an SCM case library that spans a wide variety of meteorological regimes over ARM observatories, diagnostic tests could be applied across these cases, allowing ARM data to be used in a standard way to perform rapid tests on model parameterization perturbations. In this way, the ARM SCM case library would serve as a testbed for efficient model testing and development across a range of conditions.

While we expect that SCMs will continue to provide a valuable link between ARM observations and global-scale models, it is also becoming increasingly meaningful to compare ARM measurements to a global-scale model directly as the resolution of these models increases and with the ability to run a model with increased resolution over a particular domain. For example, the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) will be available for further development and refinement on 3-km resolution, where ARM data have the potential to be assimilated or exercised for validation. Furthermore, E3SM and other models have the ability to run using a regionally refined mesh, i.e., able to overlay within an ARM observing domain. Running a global-scale model at high resolution over an ARM site would provide a framework very much like LASSO with a direct connection between ARM observations and a global-scale model. We propose to pursue projects with modeling centers to carry out this type of direct observation-model comparison.

ESMs run at high resolution or SCMs run over an ARM site represent model configuration that help link ARM data to ESMs. A precondition for this work, or any effort to apply ARM data to model output, is to ensure that the model output has the same physical meaning as the measurements. ARM typically works to generate higher-order data products to achieve this, but in some cases it may be more effective to modify the model output to mimic a measurement. For example, an instrument may have sensitivity constraints that limit its ability to observe the full natural range of a parameter, whereas a model does not. Instrument simulators have long been used as a solution to this problem. In an instrument simulator, the instrument response is applied to the output field in a model and the model generates a parameter that is more directly comparable to a physical measurement. Simulators have been developed for ARM instruments (e.g., Zhang et al. 2018) but more could be done. We propose engaging with the modeling community to develop a strategy for developing instrument simulators that would be most effective in confronting model simulations with ARM data.

T4.3 Leverage long-term ARM data sets from fixed-location observatories for model evaluation

ARM has now been operating at the Southern Great Plains for 28 years and on the North Slope of Alaska for 22 years. These long-term data sets provide an opportunity to observe many instances of meteorological phenomena, interannual variability, and trends, all of which are potentially highly valuable to the modeling community. However, application of these long-term data sets to model applications requires close attention to issues such as changes in calibration procedures, measurement uncertainties, and changes in instrumentation. Engagement with the modeling community will provide insights regarding how to make these long-term data sets most useful and to remain useful in the future.

T4.4 Use Observing System Simulation Experiments (OSSEs) to inform the optimum deployment and operation of ARM instruments for specific science goals

The activities discussed in this section so far have focused on how to apply ARM data to the evaluation of models more efficiently, but models can also be used to inform measurement strategies. OSSEs have been used extensively in the weather forecasting community to understand the impacts of assimilating new measurements into forecast models. An AI-informed OSSE has potential to change the way that ARM develops instrument scan strategies and siting instruments. Training AI systems on existing data sets, such as ARM, weather radar, and satellite data, coupled with high-resolution modeling, can inform field campaign deployments, instrument siting, and aircraft flight patterns.

Summary and Look Ahead

ARM has been providing state-of-the-art atmospheric measurements to the science community for the past 28 years with a mission to enhance the understanding of atmospheric processes and the representation of those processes in earth system models. Throughout its history, ARM has continually expanded and advanced measurement capabilities to better serve the science community toward fulfilling this mission.

In this document we have outlined a vision for the next five to ten years that is based on needs expressed by the science community and the facility enhancements that we believe are necessary to address those needs. This document identifies a number of new capabilities but the overarching vision that ties the themes together is to increase the impact of ARM instruments on advancing science issues relevant to DOE and the broader science community. This overarching driver led to the sequence of focus areas beginning with filling measurement gaps and increased attention to data analysis. Work on ARM data services will be required to support this analysis and to better enable the user community to engage with increasingly complex ARM data. Finally, with the disparity in spatial scales and the inherent separation between the observation and modeling communities, we have laid out thoughts on how to increase the use of ARM measurements by the earth system modeling community.

Within these broad themes, this decadal vision identifies specific examples of how progress can be made in each area. In the coming years we expect that specific priorities will shift as needs of the community are clarified and evolve.

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Appendix A: Science Drivers and Community Needs

ARM continually engages with the science community and needs will evolve but this section briefly outlines needs and opportunities that have been expressed over the past several years.

Data Needs to Support Current Atmospheric Science Issues

While the ARM facility serves the broad atmospheric research community, it is most tightly linked to the DOE Atmospheric System Research (ASR) program. ASR supports research that advances understanding of processes among aerosols, clouds, precipitation, radiation, thermodynamic and dynamic structure, and the land surface. These applications span a broad range of physical phenomena so alignment with ASR priorities is often also supportive of broader community needs.

The ASR program is currently organized into four science working groups that focus on components of the broader set of processes:

- Aerosol Processes
- Warm Boundary-Layer Processes
- Convective Processes
- High-Latitude Processes

ARM has been engaging with these working groups, facility constituent groups representing aerosol and cloud processes, and groups from the broader science community to identify important science gaps that ARM is well positioned to support. Through these discussions, a number of needs have been identified. Important examples of these needs include:

for Aerosol Processes

- Size distributions spanning the full range of aerosol particles (from a few nanometers to a few 10s of micrometers)
- More complete information about aerosol composition
- Increased frequency of ice nucleating particle measurements
- Vertical profiles of aerosol properties
- Wide range of aerosol measurements (e.g., detailed composition and size distribution) to constrain models.

The aerosol processes group also identified needs for structural change including a greater focus on intensive operation periods, during which more complete sets of aerosol measurements could be obtained. They also identified a need to spend more time characterizing measurements through detailed analysis and intercomparisons with instruments from other networks.

for Warm Boundary Layer Processes

- Joint measurements of cloud droplet and precipitation properties
- Robust measurements of boundary-layer structure including vertical motion
- Measurements of heat and moisture fluxes over the underlying surface (ocean and land).

for Convective Processes

- Co-variability of convective dynamics and cloud microphysics
- High-quality retrievals of ice properties
- Rapidly evolving cloud structure
- 3D thermodynamic environment
- Measurements of convection in varying meteorological regimes.

for High-Latitude Processes

- Detailed information about microphysical properties (including phase)
- Ice properties
- Surface fluxes/energy budget over heterogeneous surfaces
- Assessment of local sources versus long-range transport of water, heat, and aerosols.

Each of the cloud areas also identified the need for co-variability of aerosol properties with cloud microphysical properties. The combined cloud and precipitation constituent group also identified needs for structural changes including the use of open-source software to facilitate the implementation of advanced data processing algorithms and generally improve efficiency within the community by facilitating code-sharing.

Several of these needs represent significant measurement challenges. In some cases, such as the measurement of cloud droplet properties in the presence of precipitation, new measurement capabilities may need to be developed. In other cases, such as detailed measurements of aerosol composition, ARM may need to collaborate with the research community to augment ARM measurements with research-grade instruments for intensive periods.

However, we expect that significant progress can be made toward many of these measurement needs through careful implementation and subsequent analysis of existing ARM instruments. Therefore, looking ahead at the next 10 years, ARM will have a particular focus on extracting information from existing ARM instruments through operations coordinated toward specific science goals and an increased emphasis on data analysis.

Engaging with the Modeling Community

In considering how ARM can enhance its impact on science, it is also important to consider how ARM measurements can most effectively impact model development. The use of ARM data for the advancement in understanding of atmospheric processes is indirectly beneficial to atmospheric model development, but additional steps can be taken. DOE held a workshop in 2015 to identify opportunities to enhance the linkages among ARM measurements, ASR research, and DOE modeling activities (U.S. Department of Energy 2016). Specific actions identified at that workshop include:

- Collaborate on problem areas in model performance with a focus on priorities that can best be informed by ARM observations
- Focus on model-forcing data sets and other parameters that characterize the environment for relating local measurements with the larger domain
- Construct virtual field campaigns that organize existing data around science themes
- Explore impacts of surface heterogeneity on the atmosphere
- Focus on statistical relationships among parameters
- Implement a multi-scale framework linking models and observations
- Make use of instrument simulators to relate observations to model output.

ARM has made progress on each of these areas including the development of the LES modeling framework (Gustafson 2020); however, much more could be done. Perhaps most important is fostering and developing relationships between ARM and modeling groups to ensure that ARM efforts are applied in this arena in the most effective ways.

Appendix B: Continued Engagement with the Science Community

The overarching themes of the ARM Decadal Vision cover a progression from strategies to enhance the impact of ARM measurements, to data analysis activities and data services, to strategies to support the use of ARM data for model development. Examples are outlined for each theme that align with needs that have been identified by the science community, but these specific examples are likely to evolve. A brief summary of current science priorities was given in the "Science Drivers" section. Those science drivers were based on several workshops but are also consistent with messages we have heard from the community over the past few years.

Looking ahead, we expect that science priorities will evolve. To remain engaged with evolving priorities, it will be important to convey the scope of current ARM activities and provide a mechanism for the community to comment on those priorities and suggest new directions. Discussions of measurement needs with the Cloud and Precipitation Measurement and Science Group led to a framework that helps to document those needs and develop priorities. The framework involves defining the following elements for each identified measurement (or data product) need:

- Overarching science question
- Specific measurements or data products needed to address the gap
- Proposed strategy to address the gap
- Maturity of the proposed strategy (is research and development required?)
- Readiness of ARM to implement the strategy (e.g., in an appropriate location)
- Impact of implementing this capability
- Link between the proposed activity and modeling.

Using this supporting information for identified needs, ARM will develop specific priorities and communicate those priorities through the ARM website. Going forward, ARM will solicit input regarding needs on an ongoing basis with significant updates to the priorities expected annually. To ensure that input reflects broad community needs, ARM will be looking for input from organizations that represent those needs, including the ASR working groups as well as science team leads from other programs. Selected actions as well as submitted ideas and the submission form for new ideas will be available on the "Future Directions" portion of the ARM website.