DOE/SC-ARM-TR-270

ATMOSPHERIC RADIATION MEASUREMENT
USER FACILITY

# Decadal Vision Progress Report

*Progress Towards Goals Outlined in the 2014 Decadal Vision*

**April 2021**

ARM

U.S. DEPARTMENT OF ENERGY | Office of Science

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## DISCLAIMER

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# Progress Towards Goals Outlined in the 2014 Decadal Vision

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# Executive Summary

The Atmospheric Radiation Measurement (ARM) user facility published its first decadal vision document in 2014 (U.S. DOE 2014a). The overarching vision described in that document was to develop an integrated observation-modeling framework to accelerate the application of ARM observations for process studies and model applications. Within this large goal, ARM defined five high-level goals:

1. Establish observation-megasites at the Southern Great Plains (SGP) and North Slope of Alaska (NSA).
2. Produce routine high-resolution model simulations over domains coincident with ARM sites.
3. Continue focusing on ARM measurement excellence to support U.S. Department of Energy (DOE) climate science research.
4. Enhance data products and processes.
5. Strengthen interactions with the user community.

Over the past six years, these goals have been important factors in identifying ARM development priorities and a great deal of progress has been made in each area.

Goals 1 and 2 link most directly to enhancing the link between ARM measurements and models. In working toward these goals, ARM first developed improved spatial sampling at the SGP by expanding and upgrading supplementary sites, and at the NSA by implementing uncrewed aerial systems (UAS) and tethered balloon systems (TBS) at the NSA. Leveraging the enhanced spatial measurements at the SGP, ARM has implemented a framework for running large-eddy simulation (LES) models and has now run many simulations of shallow cumulus over the SGP.

Under goals 3 and 4, the vision document outlines a variety of opportunities to enhance the impact of ARM measurements. Following goal 3, ARM has refined operational strategies around complex instruments first implemented through the Recovery Act, provided expanded measurements at the Eastern North Atlantic (ENA) observatory to support the study of marine stratocumulus, and started down the path of replacing the Gulfstream-159 (G-1) turboprop research aircraft with a Challenger 850 regional jet. Supporting these measurement advances, ARM has also made advances in several data areas. These include the development of data products supporting modeling applications, improving the discoverability of ARM data products, and improving processes for characterizing the quality of ARM data.

The last goal deals with interactions with the user community. ARM has always had an engaged user community; however, prior to 2014, ARM had no formal mechanisms to manage those interactions, which were focused on the DOE Atmospheric System Research (ASR) program. Following the 2014 vision document, ARM established several constituent groups to formalize engagement with researchers and has made progress on reaching out to the broader community.

The purpose of this document is to review the progress made toward the 2014 decadal vision as ARM turns from that document with the release of an updated decadal vision document in 2021 (U.S. DOE 2021). The new vision document carries forward some of the same themes as the 2014 version but adds progress made over the past seven years; with evolving needs within the science community, it includes many new themes as well.

# Acronyms and Abbreviations

| | |
|---|---|
| ACE-ENA | Aerosol and Cloud Experiments in the Eastern North Atlantic |
| ACME-V | ARM Airborne Carbon Measurements-V |
| ACSM | aerosol chemical speciation monitor |
| ADC | ARM Data Center |
| AERI | atmospheric emitted radiance interferometer |
| AGU | American Geophysical Union |
| AMF | ARM Mobile Facility |
| AMSG | Aerosol Measurement Science Group |
| ANL | Argonne National Laboratory |
| AOS | Aerosol Observing System |
| APA | American Psychological Association |
| ARM | Atmospheric Radiation Measurement |
| ARMBE | ARM Best Estimate product for Modelers |
| ASR | Atmospheric System Research |
| BER | Biological and Environmental Research |
| CACTI | Cloud, Aerosol, and Complex Terrain Interactions |
| CAUSES | Clouds Above the United States and Errors at the Surface |
| DOE | U.S. Department of Energy |
| DOI | Digital Object Identifier |
| DQ | data quality |
| ENA | Eastern North Atlantic |
| ESS-DIVE | Environmental Systems Science-Data Infrastructure for a Virtual Ecosystem |
| FFT | Fast Fourier Transform |
| G-1 | Gulfstream-159 |
| GASS | Global Energy and Water cycle Exchanges |
| GEWEX | Global Energy and Water Exchanges |
| HPSS | High-Performance Storage System |
| HTDMA | humidified tandem differential mobility analyzer |
| IASOA | International Arctic Systems for Observing the Atmosphere |
| ISO | International Organization for Standardization |
| LASSO | LES ARM Symbiotic Simulation and Observation |
| LES | large-eddy simulation |
| MFRSR | Multi-filter rotating shadowband radiometer |
| MLA | Modern Language Association |
| MOSAiC | Multidisciplinary drifting Observatory for the Study of Arctic Climate |

| | |
|---|---|
| NEON | National Ecological Observatory Network |
| NGEE | Next-Generation Ecosystem Experiments |
| NOAA | National Oceanic and Atmospheric Administration |
| NREL | National Renewable Energy Laboratory |
| NSA | North Slope of Alaska |
| OPeNDAP | Open-source Project for a Network Data Access Protocol |
| OSTI | Office of Scientific and Technical Information |
| Py-ART | Python ARM Radar Toolkit |
| SGP | Southern Great Plains |
| SIRS | solar and infrared radiation station |
| TB | terabyte(s) |
| TBS | tethered balloon systems |
| THREDDS | Thematic Real-time Environmental Distributed Data Services |
| UAS | uncrewed aerial systems |
| VAP | value-added product |

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# 1.0 Introduction

The overarching vision laid out in the Atmospheric Radiation Measurement (ARM) 2014 Decadal Vision document (U.S. DOE 2014a) was to develop an integrated observation-modeling framework to accelerate the application of ARM observations for process studies and model applications. Within this large goal, ARM defined five high-level goals:

1. Establish observation-megasites at the Southern Great Plains (SGP) and North Slope of Alaska (NSA).
2. Produce routine high-resolution model simulations over domains coincident with ARM sites.
3. Continue focusing on ARM measurement excellence to support U.S. Department of Energy (DOE) climate science research.
4. Enhance data products and processes.
5. Strengthen interactions with the user community.

Over the past six years, these goals have been important factors in identifying ARM development priorities and a great deal of progress has been made in each area.

Each of these goals is associated with the central vision to better link ARM observations with models, though this is more direct for some than others. Goals 1 and 2, in particular, directly support the establishment of the integrated observation modeling framework.

# 2.0 Progress Toward Goals

## 2.1 Establish Megasites at the Southern Great Plains and North Slope of Alaska

*Augmentation of measurements at the ARM SGP observatory*

The template for the LES ARM Symbiotic Simulation and Observation (LASSO) observation-modeling framework originated in a high resolution modeling workshop held in the spring of 2014 (U.S. DOE 2014b). That workshop focused on the SGP. Recommendations from the workshop included focusing on shallow convection, establishing a set of four boundary-layer profiling facilities, and improving the SGP network of soil moisture measurements.

ARM upgraded the soil moisture network in 2015 and 2016 (Cook 2018). The new instruments provide better dynamic range, which was the key issue raised during the SGP workshop. ARM also designed and installed a set of four boundary-layer profiling stations, each approximately 50 km from the SGP Central Facility. These stations include instruments for profiling water vapor and vertical air motion as well as detection of shallow clouds. These stations were also installed in 2015 and 2016 and provide spatial information about boundary-layer structure (Mather 2016).

The workshop also recommended using scanning cloud radars to sample the spatial distribution of shallow cumulus. Subsequent analysis revealed that radar would not be suitable for observing shallow cloud fields at the SGP due to sensitivity limitations associated with very small cloud droplets (Lamer and Kollias 2015). However, following an initial field campaign, an alternative stereophotogrammetry approach has been implemented to observe the three-dimensional distribution of shallow cumulus. This technique uses pairs of cameras to determine the detailed spatial structure of broken cloud fields. This network was installed in 2017 and is beginning to provide detailed information about the distribution of shallow cumuli (Romps and Oktem 2018).

*Augmentation of measurements on the North Slope of Alaska*

A second workshop was held in 2014 to explore opportunities to enhance measurements on the North Slope of Alaska, again with the high-level goal of accelerating the application of ARM measurements to atmospheric process studies and model applications (U.S. DOE 2015a). The workshop provided an opportunity to review science goals for the region and strategies to enhance measurements to achieve those goals. Measurement priorities particularly focused on the need to obtain information about vertical atmospheric structure and horizontal heterogeneity.

There has not been a clear path to significantly extending ground-based measurements, so the emphasis on extending measurements on the North Slope has been through aerial measurements including tethered balloon systems (TBS) and unmanned aerial systems (UAS), with a particular emphasis on the Oliktok Point site. Oliktok is unique in terms of its potential to support TBS and UAS operations because DOE manages a region of restricted air space over the Oliktok observatory and a warning area that extends from just north of Oliktok out over the Arctic Ocean toward the North Pole.

Over the past five years there have been extensive TBS and UAS activities by ARM and research partners including the Oliktok site science team (de Boer et al. 2018). These missions have mainly involved small UAS, which provide information about air temperature and humidity along with surface temperature, and TBS, which are capable of carrying more instruments. TBS has been used extensively at Oliktok to obtain profiles of the atmospheric thermodynamic state, turbulence, aerosol properties, and even cloud properties (Matrasov et al. 2017).

In 2015, ARM also worked with the scientists who had been measuring carbon profiles over the SGP observatory using a Cessna aircraft to fly a mission over the NSA region using the Gulfstream-1 (G-1) aircraft. That ARM Airborne Carbon Measurements-V (ACME-V) mission provided useful information about the spatial distribution of aerosol and their impact on cloud properties.

Characterization of arctic aerosol is critical to understanding processes that influence arctic mixed-phase stratocumulus clouds. Increasing oil and gas exploration in the Arctic has raised concerns about the effects of absorbing aerosols from diesel soot and other pollutants on AMPS and the rapidly changing sea ice. The ARM-ACME V campaign deployed the G-1 aircraft to sample properties of clouds, aerosols, and greenhouse gases in the North Slope of Alaska region between Prudhoe Bay, Toolik Lake, Atqasuk, and Utqiaġvik (Figure B1.1). Using ACME V observations, Maahn et al. (2017) compared the relatively pristine air at Utqiaġvik with the highly polluted air at Oliktok caused by activities in the nearby Prudhoe Bay oil fields to understand the role of anthropogenic emissions on cloud properties. They found that Oliktok had twice the number of condensation nuclei and increased black carbon concentrations compared with Utqiaġvik, which resulted in significantly smaller cloud droplets and suppressed drizzle at

Oliktok. Since the air in the NSA region is relatively clean, even small amounts of anthropogenic emissions can have a large impact. Creamean et al. (2018) characterized regional and long range aerosol sources in the NSA region during ACME V. Local sources from oil extraction activities, regional wildfires, and to a lesser extent long-range transport contribute to the arctic haze. Previously it was assumed that the Arctic was relatively pristine.

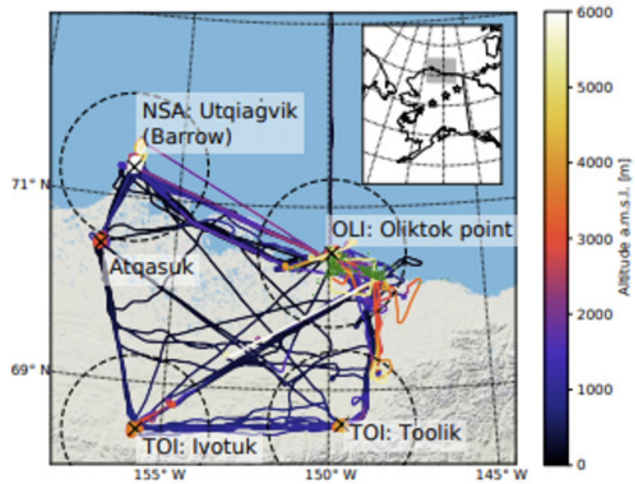


**Figure 1**. DOE G-1 flights during ACME V help characterize the impact of local industrial emissions on arctic clouds, revealing that mean droplet size is reduced when emissions increase, which contributes to changes in cloud radiative feedback in the changing arctic climate. From Maahn et al. (2017).

## 2.2 Produce High-Resolution Model Simulations over ARM Sites

The expansion of observations at SGP and NSA described in the previous section was part of a strategy to bridge ARM measurements with large-scale models. The other part of the strategy was to implement high-resolution model simulations over ARM sites. A key recommendation of the 2014 SGP workshop (U.S. DOE 2014a) was to undergo a pilot study before formally implementing an ARM modeling system. The purpose of the pilot study was to establish the optimum design for this modeling system. In early 2015, an award was made for a pilot study project, which ultimately became the LASSO framework. By 2016, the LASSO team was running simulations of SGP shallow convection cases using several large-eddy simulation (LES) models. The team reached out to the community during the development phase through formation of an ad hoc constituent group, engagement at conferences, the ARM website, and targeted emails.

The LASSO team formalized their design in 2017 and have been running simulations for the summer shallow convection seasons at SGP for the years 2015-19. Over the past five years, LASSO has run over 1,000 LES simulations for 95 case days with a focus on shallow convection at the SGP. LASSO provides a unique capability for users in delivering a library of LES simulations that have been evaluated against ARM data and are made available to users with associated measurement data through a specially designed ordering interface. The simulations provide a useful test for the underlying ARM observations, which has led to improved characterization of parameters, such as liquid water content, for LASSO periods.

LASSO was originally used to study shallow convection at the ARM SGP site but we always intended to expand LASSO to additional ARM locations and meteorological regimes. After input solicitation from the science community, we selected deep convection as the next target for LASSO. In particular, LASSO will be configured to simulate cases observed during the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) mobile facility deployment to Argentina in 2018-2019. The goals for running LASSO for convective events observed during CACTI include studying the dynamic structure and microphysical processes in deep convection. We expect that these simulations will draw in a broader portion of the research community and will be valuable for advancing the science goals of the CACTI campaign.

The one explicit goal from the 2014 Decadal Vision that has not been met is the implementation of LASSO over the North Slope of Alaska following development and application at the SGP. While there continues to be interest in ARM running arctic simulations, other targets for ARM simulations have arisen that are more ready for an intensive modeling activity (Gustafson et al. 2019). Based on this community engagement and associated assessment, the ARM Decadal Vision identifies a plan to take on deep convection as the next target for LASSO and to pursue the generalization of LASSO so that it can be applied to a variety of science themes and ARM locations.

## 2.3 Continue Focusing on ARM Measurement Excellence

A major focus of the 2014 Decadal Vision was the establishment of the observation-modeling framework described in the previous two sections; however, the document also described the need to continue focus on existing capabilities. The central capability of ARM is its broad array of measurements and this portion of the Decadal Vision identified four aspects of the ARM measurement network for focused attention:

- Application of recently added ground-based measurement capabilities to best meet the needs of the science community.
- Directed use of the ARM Mobile Facilities to advance high-priority science.
- Application of the new Eastern North Atlantic (ENA) observatory to study marine stratocumulus.
- Adaptation of the ARM Aerial Facility to better support the ground-based observatories.

*Application of ground-based measurements to meet community needs*

Between 2009 and 2011, ARM greatly expanded its measurement capabilities through funding from the American Recovery and Reinvestment Act of 2009. This infusion of capabilities particularly advanced our wherewithal for measuring cloud and aerosol properties. The advanced instrumentation provided the means to break through roadblocks that had been limiting the ARM user community for years. However, the sudden infusion of instrumentation also posed some challenges for instrument operation, data analysis, and product development.

The most complex instrument systems emerging from the Recovery Act period are the scanning radars and the aerosol observing systems. To identify the optimal strategy to manage these instruments, ARM has engaged with the user community through constituent groups and has established plans to optimize the science impact of these instruments.

In 2016, ARM developed a plan to improve the management of its radar network. The plan outlined a strategy to focus instrument maintenance and characterization effort on specific radars on a 2-3 year repeating period. The initial focus of this plan was on scanning radars at the ARM ENA site, which was to host the ACE-ENA stratocumulus campaign the following year, and the site at Oliktok Point, which shared the same vintage radar system as ENA. In analyzing the radar data availability, we found that these efforts were effective in that the radars receiving this attention exhibited significantly better performance than had been experienced with scanning radars previously. Additionally, the radars were very well characterized through a newly developed field calibration procedure. However, the experience also revealed that without sustained effort, scanning radars would quickly exhibit operational failures.

During the 2017 review, the team was asked to update their plan. The 2017 plan again set priorities for ARM radars, which were largely dictated by upcoming radar-intensive field studies at the SGP and the first ARM Mobile Facility, which was slated for the CACTI campaign in Argentina with a focus on deep convection. Preparing for these campaigns was an all-hands effort for several months but resulted in successful deployments for each of the radar systems. The Argentina campaign had high instrument up-time and has resulted in the best characterized radar data sets to date (Hardin et al. 2020).

The experience gained through the development and application of the radar plan is teaching us how to best manage deployments of the most complex ARM instruments and is helping us find the right balance between operations and analysis efforts for these instruments. In some cases the result of this assessment is expected to lead to reduced operations and will inform the scope reduction process.

A great deal of effort was also invested over this period to improve the effectiveness of ARM aerosol measurements. The scope of this work was developed through engagement with the aerosol science community, which was facilitated by the implementation of the Aerosol Measurement Science Group (AMSG). The AMSG brings together community scientists and ARM staff to identify needs for improvement in the operation and processing of ARM aerosol measurements and the review of strategies to address those needs (AMSG Charter). In 2017, ARM developed an implementation plan that was based in large part on recommendations from an AMSG workshop (Mather et al. 2018). Significant progress has been made toward the goals in that plan including implementing a new aerosol drying system, harmonizing data products across instruments to support a unified particle size distribution, and advances in improving the quality of humidified tandem differential mobility analyzer (HTDMA) measurements.

Work on complex measurements, including radars, aerosol instruments, and others continues and is captured in the updated Decadal Vision (U.S. DOE 2021) in terms of new measurement strategies and a focus on data characterization.

*Directed use of the ARM Mobile Facilities*

An idea was put forward in the 2014 vision to constrain AMF deployments to ensure that remaining high-priority meteorological regimes would be sampled. To date, the open proposal process continues to be viewed as effective and no such constraints have been placed on deployments of the first or second Mobile Facilities. However, the concept is being applied to the third ARM Mobile Facility, which is intended for longer-term deployments. In 2018, DOE convened a workshop on enhancing the science impact of the Mobile Facilities (U.S. DOE 2019). This workshop included an assessment of regions that were identified as high priority by contributors to the workshop (either through attendance or in response to a public solicitation for whitepapers).

This workshop led to the decision by DOE to move the AMF3 from Oliktok to the Southeastern U.S. This transition will begin in 2021 and the AMF3 is expected to be operational in its new location by the end of 2022. Like the Oliktok deployment, this deployment of the AMF3 is intended to last for about five years.

The Southeastern region was compelling because it is expected that deep convection there is often locally forced (versus advected from an upstream source) and it is a source region of secondary organic aerosols. Thus, this region is expected to provide an excellent opportunity for convection and aerosol process studies. Additionally, the site science team that was selected for this deployment did an excellent job highlighting the importance of land-atmosphere interactions in this region. The team actually includes leaders from the cloud, aerosol, and land-surface science communities. This early focus on interdisciplinary science is already drawing in scientists from outside of the traditional atmospheric research community.

In addition to being multi-disciplinary, the Southeastern U.S. science team has also been proactive in reaching out to the community, including a talk at the annual Terrestrial Ecosystem Science team meeting and a proposal for a townhall at the American Geophysical Union (AGU) annual meeting. The team is also working with ARM staff to identify other networks, such as the National Ecological Observatory Network (NEON), that provide opportunities to engage with communities from other agencies. We also note that this region is known for severe weather and is of considerable interest to the forecast community.

Given these factors, we expect the Southeastern U.S. site to provide observations that will support and draw together scientists from a broad range of disciplines. We currently plan for the Southeastern U.S. site to commence in the fall of 2022 and operate for approximately five years.

*Application of the Eastern North Atlantic observatory to study marine stratocumulus*

The ENA observatory was established on Graciosa Island in the Azores archipelago in 2013 and was further instrumented through 2014. The focus of this site is the study of marine stratocumulus, though the Azores experiences a wide variety of meteorological conditions. This long-term observatory deployment followed a mobile facility deployment to the same location in 2009-2010 (Wood et al. 2015). A significant focus of work to date at the site has been the properties of marine stratocumulus (e.g., Lamer et al. 2019).

In 2017-2018, the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) field campaign was carried out at the ENA observatory. This campaign focused on marine stratocumulus and included a pair of one-month deployments of the ARM G-1 research aircraft. The campaign saw the collection of scanning radar data from both the ARM cloud and precipitation radars as well as a variety of guest instruments. It is expected that the wealth of remote-sensing and in situ measurements provided by ACE-ENA will motivate significant science advances in marine stratocumulus processes and aerosol-cloud interactions. Some of this work has already been highlighted in an ACE-ENA workshop held in early 2019 and at the 2019 ARM/Atmospheric System Research (ASR) joint meeting.

*Adaptation of the ARM Aerial Facility to support ground-based observatories*

In 2014, a workshop was held to study aerial measurement needs (U.S. DOE 2015c). Between that workshop and the NSA workshop around that time (U.S. DOE 2015b), several things were recognized:

- A need for continued aerial measurements to augment the ARM ground-based observatories.
- A need for more routine aerial measurements, particularly at the NSA because of the challenge in getting spatial information in that region in other ways.
- UAS could be valuable to obtain routine measurements.
- The G-1 would need to be replaced within 6-7 years due to age.

The implementation of UAS, as well as TBS, on the North Slope of Alaska was discussed above in section B.1 and investigation into a possible successor to the G-1 began shortly after the aerial workshop. The process to replace the G-1 involved a formal assessment of the need for this capability and an analysis of alternatives. The G-1 was ultimately retired in early 2019 following a decade of service to ARM and a Challenger 850 aircraft was purchased in June of that year.

The Aerial Facility team is currently modifying that aircraft to prepare it for research applications. The Challenger will enable in situ sampling over a broader range of altitudes than the G-1 and will also provide increased payload capacity and endurance.

In terms of measurements, the first order of business will be to implement instruments used on the G-1. However, because of significant interest in expanding these capabilities, in March 2020 a workshop reviewed 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 Challenger aircraft. Over the coming few years ARM will identify opportunities to enhance aerial measurement capabilities by matching high-priority science needs with new measurement capabilities. The combination of improved capabilities for the Challenger with expanded and enhanced instrumentation is expected to increase the impact of the ARM Aerial Facility.

## 2.4 Enhance Data Products and Processes

Along with identifying areas to improve the impact of ARM measurements, the 2014 Decadal Vision identified opportunities to enhance ARM's impact through the development of data products and processes. Six separate areas for development were identified:

- Data processing to bridge observations and models
- Improving the discoverability of ARM data
- Improving the characterization and communication of data quality and uncertainties
- Use of DOIs to link data citations
- Ensuring the security and stability of ARM data and software
- Integration of ARM data with other DOE Biological and Environmental Research (BER) data sets.

*Data Processing to Bridge Observations and Models*

A significant focus in this area has again been support of LASSO. The implementation of the LASSO modeling framework required the development of enhanced data products used as model input (e.g., large-scale forcing products) and metrics and diagnostics data sets for model evaluation (Gustafson et al. 2020). For example, atmospheric emitted radiance interferometer (AERI)- and Raman lidar-derived temperature and humidity profiles were merged to provide continuous profiles, and AERI and microwave radiometer retrievals were merged to provide a more comprehensive liquid water path range. Many of these merged and hybrid products are packaged as part of simulation data bundles that can be customized by users using the interactive bundle browser available through the ARM Data Center (ADC). Bundles consist of a set of metrics, diagnostics, simulation output, and retrieved data products and can be filtered and packaged for cases of interest to the user.

Beyond LASSO, the ARM Best Estimate product for Modelers (ARMBE) synthesizes atmospheric quantities from other ARM value-added products (VAPs), such as thermodynamic profiles, cloud properties such as cloud occurrence and liquid water path, surface broadband radiation, sensible and latent heat fluxes, and soil properties. ARMBE was extended to additional long-term observatories, such as NSA and the former Tropical Western Pacific locations, over the last several years and is continuing to be extended to other ARM locations.

The development of new derived datastreams can be a limiting factor in using ARM data for model applications. A mechanism that was identified to address this in 2014 was the use of open-source software. Open-source software development has the potential to improve efficiency by encouraging code sharing within ARM and with the science community. An early open-source project for ARM was the Python ARM Radar Toolkit (Py-ART), which is a collection of open-source Python modules containing a growing collection of weather radar algorithms and utilities designed for visualizing and manipulating scanning radar data (Helmus and Collis 2016). ARM has recently adopted an open-source Python library to support data merging and visualization along with other applications and is implementing a set of Github organizations to encourage community engagement. Application of collaboration through open source practices is explored in the updated Decadal Vision.

*Improve discoverability of ARM data*

The ARM Data Discovery tool (https://adc.arm.gov/discovery/) helps scientists to find and access these data sets. During FY2019-20, this tool underwent a major design revision to improve the user experience. As part of this revision, the ADC team reached out to over 30 stakeholder teams and gathered over 100 recommendations. In addition, the ADC team also conducted usability testing using the University of Tennessee's User-eXperience Lab. Using these recommendations, a design was developed and reviewed by stakeholders. A completely new Data Discovery tool was developed with modern software architecture using continuous integration methodology.

The ARM Data Discovery tool (Figure B4.1; https://adc.arm.gov/discovery/) helps scientists to find and access these data sets. A redesigned tool was released in 2020. To guide the new design, ARM reached out to over 30 stakeholder teams and gathered over 100 recommendations, and conducted a usability test using the University of Tennessee's User-eXperience Lab. Some of the key findings from the stakeholder reviews are: search results returning too many results at the parameter level by default, information overload on the search results page, no option to set user preferences, and lack of details about datastreams. As a result, a completely new Data Discovery tool was developed with modern software architecture using continuous integration methodology to add user requested features in a phased approach.

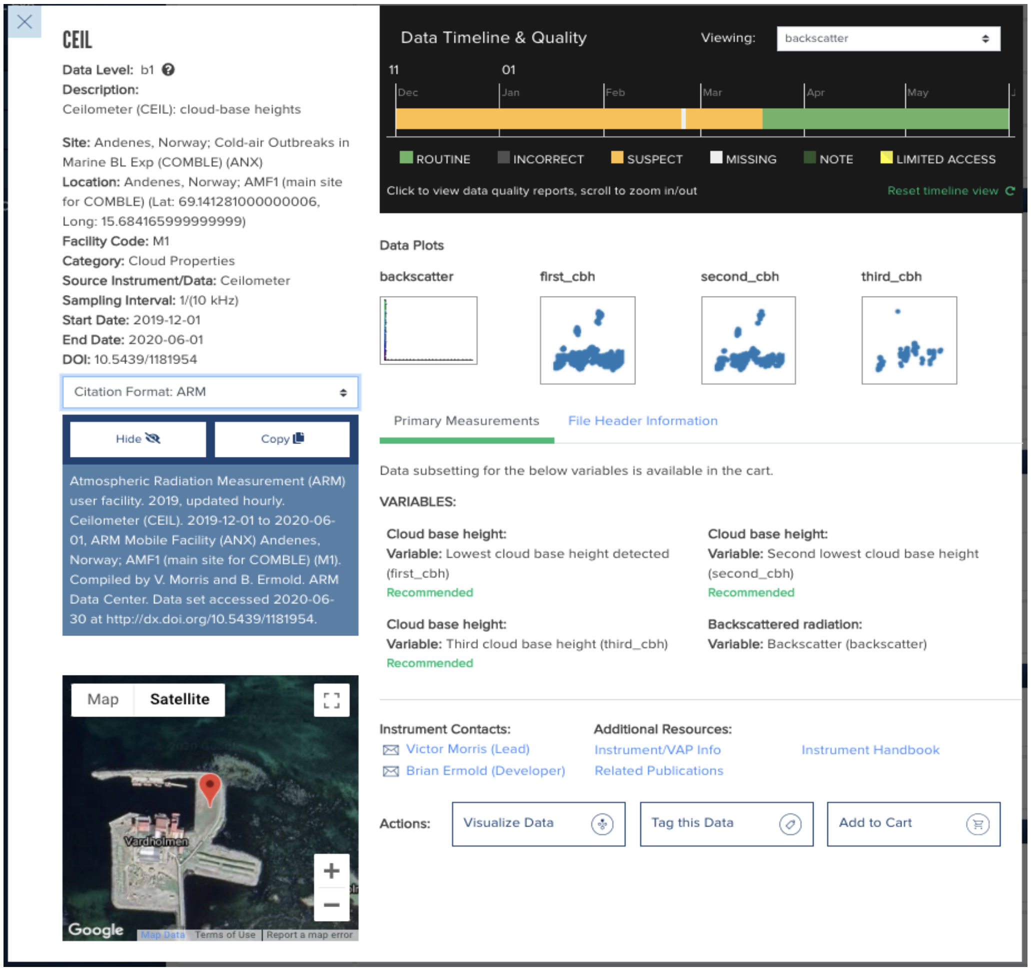


**Figure 2.** The upgraded Data Discovery Tool allows users to drill into specific datastreams to learn more detailed information.

The new Data Discovery interface, released in May 2020, includes a powerful faceted search capability that allows users to search for data by measurement category, location, data source, and several other categories. The interface integrates data quality information visually and by enabling the user to filter ordered data based on data quality reports. Detailed information about the data and who to reach for assistance is easily displayed. Other features include: a guided search for novice users, data access and delivery options (i.e., Thematic Real-time Environmental Distributed Data Services [THREDDS]/Open-source Project for a Network Data Access Protocol [OPeNDAP], Globus Online), automated and near-real-time data access and web service, data citation generator, advanced visualizations, and data analysis for identifying data of interest. The new interface also allows users to save and reorder data that were requested in the past using the My Accounts feature. Using the continuous feedback and integration methodology, ARM will continuously upgrade the newly developed tool to meet and exceed the user needs. The phase II upgrade, started in July 2020, will add features like: spatial data search, data filter using data quality flags, and search based on data epoch.

*Improve the characterization and communication of data quality and uncertainty*

The combination of better oversight and improved data quality monitoring and reporting tools have led to a substantial decrease in time to resolve instrument problems and communicate the data quality effects to end users. The Data Quality (DQ) Office continuously works to add new and improve existing capabilities as it relates to problem detection. As such, they have been implementing email alerts that will notify interested parties when a problem is detected by the automated software (examples in Figure B.4.1). This provides a nearly instantaneous alert to problematic data instead of waiting for manual review by the DQ analyst. Some of these tests have the capability to detect problems that are not easily discernible by the human eye, such as the “FFT Shading Test” that can detect shading issues with shadowband radiometers.

In addition, ARM instrument mentors are increasingly involved in intercomparison studies to help improve the characterization of their instruments. The single-particle soot photometer was involved in an intercomparison at the Paul Scherrer Institut Calibration Centre for Soot Measurements prior to the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) campaign. Two additional aerosol-related intercomparison studies were planned for 2020 but have been delayed due to COVID-19 travel restrictions. A substantial effort has also been made to characterize the aerosol chemical speciation monitor (ACSM), which has resulted in the development of a second data users report that will be posted on ARM’s website as a technical report. The National Renewable Energy Laboratory (NREL) has also invested in substantial efforts towards the characterization of different radiometers under an array of conditions and configurations. This has helped inform the upcoming transition of the broadband radiometer system to be upgraded with the best-in-class radiometer.

**Table 1**. Automated data quality checks implemented by the ARM Data Quality Office to streamline the identification of instrument operation issues.

| Test | Description |
|---|---|
| ACSM/CO Clog Test | Checks inlet pressure fields for marked decreases to catch potentially critical orifice clogs. |
| CO Pressure Test | Checks AOS CO pump pressure to catch pump failures. |
| FFT Shading Test | A Fast Fourier Transform (FFT) method to detect shading problems with the multi-filter rotating shadowband radiometer (MFRSR; Alexander 2007). |
| MFRSR-SIRS Short Direct Normal Test | Short direct normal variables from the MFRSR and solar and infrared radiation station (SIRS) are compared and tracked over time to determine potential SIRS solar tracker issues. |
| SIRS Test Suite | Automated tests and alerts including nighttime offsets, logger checks, ventilator tachometer checks, and serial number consistency for SIRS radiometers. |
| Stereographic Camera Scene Change | Code provided by the mentor was used to calculate when the camera scene may have shifted. |

The quantification of uncertainty continues to be a challenging topic despite work in this area. Initial efforts involved the publication of baseline measurement uncertainties for most ARM measurements in two technical reports (Campos and Sisterson 2015, Sisterson 2017). The ARM translators, responsible for the development of VAPs, have begun working with the ARM Standards Committee to define standards for uncertainty. Recommendations include adding uncertainty to a file as an ancillary variable or attribute; providing uncertainty information automatically, not optionally, at download; and sending emails to users if uncertainty information is updated. The translators have also described a strategy that focuses on determination of uncertainties for a strategic set of measurements, which would have significant downstream impacts (Riihimaki et al. 2018). There has not been significant progress on this strategy because it requires a significant effort on measurement analysis. This is a broad need identified as one of four themes in the updated Decadal Vision.

*Use DOIs to link data to citations and background information*

ARM established a data citation strategy based on Digital Object Identifiers (DOIs) for the ARM data sets in order to facilitate citing continuous and diverse ARM data sets in articles and papers. This strategy eases the tracking of data provided as supplements to articles and papers. Additionally, it allows future data users and ARM to easily locate the exact data used in various articles. Traditionally, DOIs are assigned to individual digital objects (a report or a data table), but for ARM data sets these DOIs are assigned to ARM data products. This eliminates the need to create DOIs for numerous components of the ARM data product, in turn making it easier for users to manage and cite the ARM data. In addition, the ARM data infrastructure team, with input from scientific users, developed a citation format and an online data citation generation tool for continuous datastreams. This citation format includes DOIs along with additional details such as spatial and temporal information.

The key improvements to the DOI in the last three years include: a new option within the data product registration form (Online Metadata Editor) for assigning DOIs to field campaign and PI data products, a new strategy to assign DOIs for radar datastreams, options to extract citations using commonly used formats such as American Psychological Association (APA), Modern Language Association (MLA), and Chicago formats, customized citations for user-ordered datastreams, finding citations for past data downloads within the MyAccounts page, linking the publications with corresponding ARM data using DOE's Office of Scientific and Technical Information (OSTI) Data Explorer, and linking citations and data with Google Data Search.

*Ensure the security and stability of ARM data and software*

During FY2017-18, The ADC completely rewrote the legacy data verification and archival software workflow with Python, which reduced the manual troubleshooting efforts by over 70%. This modular software also allowed ADC to extend the data backup to Argonne National Laboratory (ANL)'s High-Performance Storage System (HPSS). Since early FY19, the ADC team started using network-based, automated offsite data backup at ANL HPSS for any new incoming data files. In addition, the ADC team backed up over 900 terabytes (TB) of historical data and continues to backfill the remaining files.

During FY2018, based on DOE guidance, ARM Data Services carried out a major consolidation and streamlining of end-to-end data flow. These tasks included: 1) Identifying and implementing improvements to various operations, servers, processes, databases, tools, and workflow that support data services; 2) Completing critical tasks such as migrating software and databases to virtual servers, removing redundant processes, streamlining and modernizing operational and metadata management tools; and 3)Simplifying workflows for managing the data ingest operations, metadata creation, and reprocessing operations.

*Integrate ARM data with other BER climate measurements and simulations*

The ADC is actively involved in improving the visibility of ARM data products in broader data clearinghouses and relevant scientific portals. As an example, users can search ARM data products in DOE's Next-Generation Ecosystem Experiments (NGEE)-Arctic data portal and OSTI Data Explorer. ARM is also a member node of the National Science Foundation (NSF)'s DataOne in which DOE's Environmental Systems Science-Data Infrastructure for a Virtual Ecosystem (ESS-DIVE) is part of the member node. By participating with DataOne, ARM is also enabling data interoperability to other members nodes such as BER's ESS-DIVE and international collaborations such as PANGAEA (for MOSAiC data sharing). With effective use of community metadata standards such as International Organization for Standardization (ISO) 19115 and Federal Geographic Data Committee, the ADC is successfully enabled data sharing and interoperability with broader data clearinghouses (Figure B.4.2) such as data.gov, google data search, and International Arctic Systems for Observing the Atmosphere (IASOA).

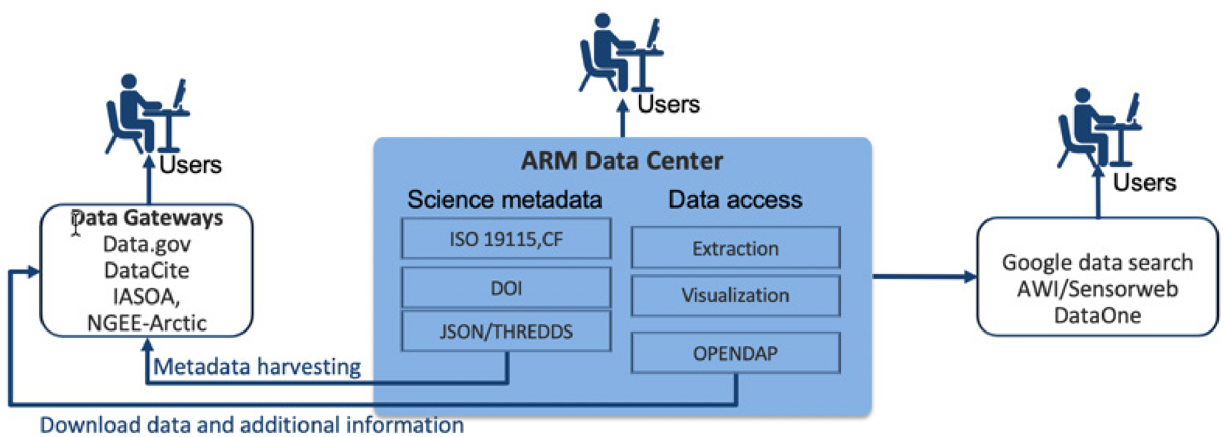


**Figure 3**. ARM uses metadata standards to enable data and metadata sharing and interoperability between the ARM Data Center and other data portals.

## 2.5 Strengthen Interactions with the User Community

In 2014, when the original Decadal Vision was published, ARM had several modes of engagement with the user community. There was a focus on participation in large meetings, such as the annual ARM/ASR science meeting and the AGU annual meeting, and focused workshops. ARM had also recently created an advisory group related to radar operations and had strong connections to the Global Energy and Water Exchanges (GEWEX) community. However, there were opportunities to strengthen that engagement. Since that time, ARM has established additional advisory groups including a User Executive Committee and two science-focused constituent groups to carry out a continuous dialogue with the user community. ARM has worked to strengthen outreach to the broader community by reaching out to a variety of related programs and external groups not associated with ARM or ASR. ARM primarily engages with this larger group through general science conferences, workshops of cross-program interest, and meetings of related programs.

The AGU fall meeting is an important annual event for ARM. The ARM booth provides an effective means of exposure for ARM and often results in discussions with scientists who have no former experience with ARM. ARM also participates in organizing sessions or town halls to provide exposure for specific activities. Recent town halls have been used to solicit feedback for the LASSO expansion and the updated Decadal Vision.

Probably the most effective means of identifying needs of other communities is to attend the meetings of those communities and engage directly with participants and meeting leaders. For example, the Clouds Above the United States and Errors at the Surface (CAUSES) modeling project was born initially out of participation in an early GEWEX Global Energy and Water cycle Exchanges (GASS) meeting. This led to a follow-on meeting at an ARM/ASR meeting and organization of a joint ARM data-modeling project that has resulted in an understanding of the underlying causes behind the mid-United States modeled temperature bias (e.g., Morcrette et al. 2018). Discussions at a more recent GASS meeting identified a need for a data repository for model-observation projects and ARM has stepped forward to provide that service. That same meeting led to the development of a joint ARM-National Ocean and Atmospheric Administration (NOAA) model parameterization project using ARM data.

ARM is also engaging with other modeling programs and with satellite programs. The general strategy for these engagements with the broader community is to identify and cultivate opportunities for collaboration. As discussed in that earlier section, these projects have led to valuable science advances and in some cases have led to relationships that have persisted for many years. These relationships are quite different than the one ARM has with ASR, but they have produced impactful outcomes.

Looking ahead, we plan to continue cultivating these inter-program relationships while we also plan to implement a more transparent mechanism to solicit feedback from both ASR and the broader science community. The recommendation, which came out of ARM's Cloud and Precipitation Measurements and Science constituent group, involves developing an online interface for leaders of science organizations such as ASR working groups, GEWEX panels, and satellite science teams, to express capability needs to ARM. Along with the needs, the form will request related information such as technical readiness and expected impact. An important component of this mechanism will be for ARM to periodically report on decisions regarding which requests will be pursued. For ASR, this will provide a more consistent and transparent mechanism to provide the type of input already being received, but for the broader community it will represent a new opportunity to express needs to ARM in a formal way.

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