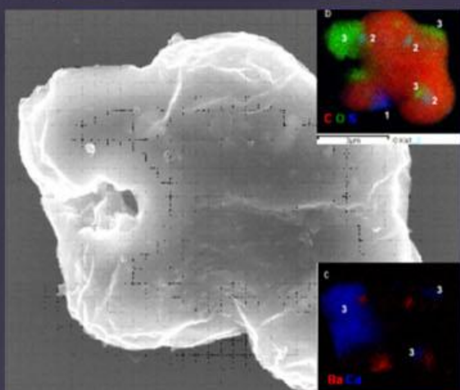

Workshop on

AEROSOL METROLOGY NEEDS FOR CLIMATE SCIENCE

Summary Report
December 2011

PREPARED BY
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NIST

FOR THE
National Institute of
Standards and Technology

Cover photo credits

First top left: *The sun photometer shown is part of a global network that measures aerosols from the ground. This station is in the Canadian Arctic. Photograph by Ovidiu Pancrati, ©2007 CANDAC; available from the National Aeronautics and Space Administration, http://earthobservatory.nasa.gov/Features/Aerosols/printall.php*

Second top left: *Two-dimensional scanning electron microscope image (a) and elemental maps (b, c) of carbonaceous particle with Ba and Ca inclusions. Photo: NIST, J. Conney*

Across center: *Satellite image from iStockphoto*

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Acknowledgements

Many thanks to all who participated in the workshop on *Aerosol Metrology for Climate* held at the National Institute of Standards and Technology (NIST) on March 14-15, 2011. The presentations and discussions that took place at the workshop provided the foundation for this report. A complete list of attendees is provided in Appendix A.

Special thanks are extended to the members of the NIST organizing committee, plenary speakers, and session chairs, listed below. A complete list of presentations is provided in Appendix B; these can be downloaded at http://www.nist.gov/mml/aerosol_metrology_for_climate_workshop.cfm

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Special thanks are extended to: the Energetics Incorporated team who provided support for workshop registration, planning, facilitation, and preparation of the final report; Donna Kimball of the NIST Materials Measurement Laboratory, for outstanding logistical and administrative support; and to Angela Ellis and the staff of NIST Conference Services for their diligent support of workshop preparation and logistics.

For more information about this report, please contact the NIST Office of Special Programs at 301-975-2000.

Preface

The National Institute of Standards and Technology (NIST) held a workshop on *Aerosol Metrology for Climate* on March 14–15, 2011, to assess the measurement science challenges faced by the atmospheric aerosol community and identify strategies to best address these challenges. The workshop brought together leading experts from industry, government, and academia to identify areas where actions are needed to enable better measurement of aerosols and further understand their potential role in climate change. This report is based on discussions held during the workshop, and will potentially guide NIST and other organizations as they set future research priorities for aerosols measurement and standards.

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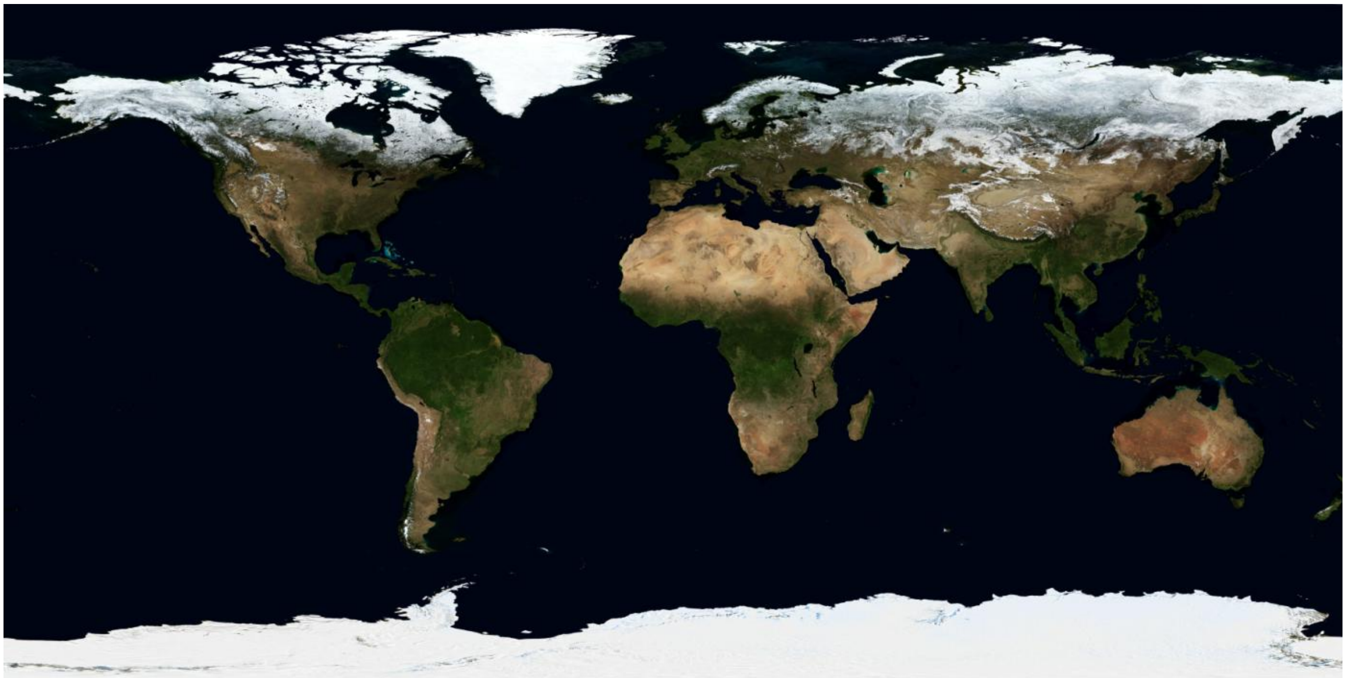
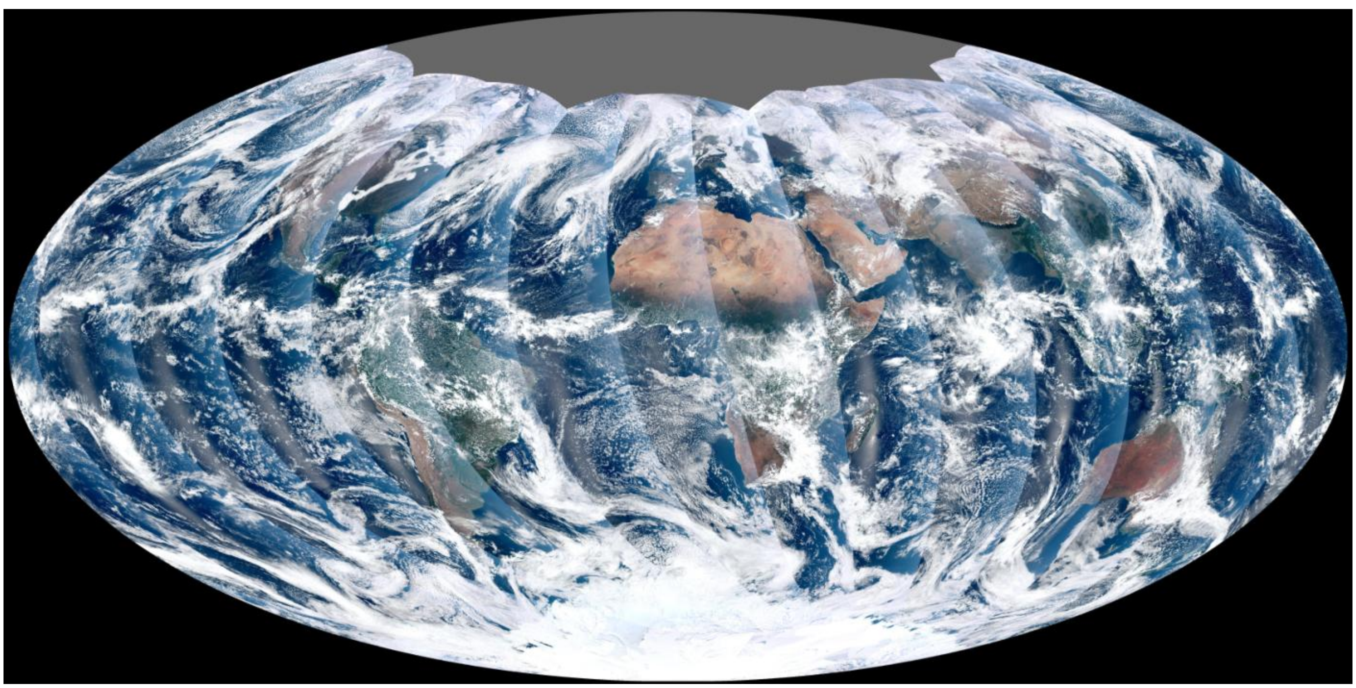


The Blue Marble: Next Generation is a series of images that show the color of the Earth's surface for each month of 2004 at very high resolution (500 meters/pixel) at a global scale. Source: NASA
http://earthobservatory.nasa.gov/Features/BlueMarble/



The Visible Infrared Imager Radiometer Suite (VIIRS) on the NPOESS Preparatory Project (NPP) satellite gets a complete view of our planet every day from a vantage 500 miles above. Shown above is the first complete global image from VIIRS taken November 24, 2011. Once VIIRS is fully operational it will produce a range of measurements from ocean temperature to clouds to the locations of fires. Source: NASA
http://earthobservatory.nasa.gov/IOTD/view.php?id=76674

1. Introduction

Background on Aerosols and Climate

Aerosols in the atmosphere have a profound influence on regional and global climate primarily through interaction with solar radiation. Atmospheric aerosols are suspensions of liquid or solid particles in air with diameters that span a wide range, from nanometers to tens of micrometers. Aerosols have a range of compositions and shapes depending on their source and how they change with atmospheric processes. In many cases, the aerosols of greatest interest are those in the 0.05 to 10 micrometer (μm) diameter size range, which are dominant in the direct interaction of aerosols with sunlight. Particles outside this size range can also have a significant impact on solar radiation. Smaller particles play a major role in cloud formation, resulting in an indirect effect on incoming solar radiation. Larger particles, generally derived from dust and volcanic sources, have substantial atmospheric mass loadings and can also have important effects on the regional and global radiation budget.

Policy makers, regulators, industrial leaders, and climate scientists require quantitative information about the physical and chemical properties of aerosol particles, particularly how these affect the interaction of aerosols with solar radiation in the atmosphere. While the importance of a range of aerosol characteristics and processes in the climate system is becoming better understood, many questions remain to be answered. For example, how much of a climate-cooling influence do aerosols presently exert? How effective are climate models at accounting for the influence of aerosols? How do uncertainties in aerosol properties affect model uncertainties, and how large are those uncertainties?

Answering these questions will depend in many cases on adequate measurement science capabilities. Atmospheric aerosols show large variations in size, morphology, chemical composition, and optical properties, and these characteristics can create complex measurement challenges.

Workshop Scope and Objectives

To explore the measurement challenges impeding characterization of aerosols for climate, the National Institute of Standards and Technology (NIST) sponsored the *Aerosol Metrology for Climate* workshop on March 14-15, 2011, in Gaithersburg, Maryland. The workshop brought together experts from government, industry and academia to explore the state of the art in measuring the size, shape, chemical composition, atmospheric evolution, and optical properties of aerosol particles. From that springboard, participants identified areas of high uncertainty in aerosol properties and generated ideas for overcoming the current challenges—information that will accelerate the development of new measurement technologies and shape the aerosol metrology climate research agenda. The workshop discussions and presentations are the foundation for this report.

Three important topical areas were covered, as shown in Figure 1.1: chemical/dimensional metrology, optical properties of aerosols, and modeling.

Figure 1.1. Workshop Topics

Chemical/dimensional metrology – measurement challenges related to understanding the chemical makeup of aerosols, which is needed to understand their absorptive and reflective radiative properties.

Optical properties – measurement science issues related to measurement and characterization of aerosols properties via optical schemes.

Modeling of aerosols – challenges related to improving the representation of processes contributing to aerosol climate effects in models and simulations.

Issues considered for each of the three areas included:

- Vision and goals for the future.
  - What are the most important properties to measure? Are existing methods/ technologies adequate? Where is innovation needed? What classes/sizes of aerosols should be investigated?
  - What would we like to achieve in aerosols metrology over the next 5, 10, and 15 years and beyond?
  - What capabilities will be needed in this area that we do not have today? What classes/sizes of aerosols should be investigated?
  - What are some specific goals or targets for aerosol metrology relevant to the topic? What are the most important properties to measure?
- Challenges and barriers to achieving the vision and goals.
  - What are the major technical impediments, challenges, limitations, or barriers preventing us from reaching the vision for the future and goals?
  - What specific measurement problems must be addressed to enable useful measurements of aerosols and their impacts on climate?
  - Are existing methods/technologies adequate? Where are innovations and improvements required?
  - What infrastructure is currently lacking to support aerosols metrology?
- Potential pathways, solutions, and approaches to overcoming the challenges and barriers.
  - What actions are needed (e.g., research, development, demonstration, reference materials and standards) and in what timeframe?
  - What will be gained by these actions?

This report is organized around the three topic areas shown in Figure 1-1, and covers workshop discussions for the key issues noted above. In addition, for each topic, a set of actionable priorities have been identified and these are outlined in detail. These represent some of the most important actions that could be taken to address the current measurement challenges for aerosols. References and additional sources for the report are provided in Appendix C.

Overall, this report provides a snapshot of the modern aerosol metrology landscape and a visionary guide for future research directions throughout the aerosol and climate community.

2. Chemical/Dimensional Metrology

Understanding an atmospheric particle's chemical composition is important as it determines the optical properties of the particle (absorptive and reflective radiative properties) and affects atmospheric chemistry in both the gas and particulate phase. Of particular interest is how aerosol chemical composition influences the ability of particles to act as cloud condensation nuclei (CCN) or ice nuclei (IN) which can impact cloud formation or patterns and lead to changes in climate. The chemical composition, size, and number of particles in a unit volume of air will define the aerosol's light extinction (scattering and absorption) properties and radiative forcing potential.

Chemical metrology involves the measurement of the chemical characteristics (e.g., elemental and subcomponent composition) of aerosols; dimensional metrology provides information about the physical size and characteristics. Chemical metrology relies primarily on spectroscopy and traditional chemical methods. Dimensional metrology requires the use of a variety of physical scales to determine dimension, with the most accurate of these being holographic etalons or laser interferometers. While techniques are available today, there are a number of challenges that must be overcome.

State of the Art

Core tools for chemical/dimensional metrology include analytical atomic spectrometry and inorganic mass spectrometry, gas and liquid chromatography, organic mass spectrometry, and chemical separations for both organic and inorganic trace analysis. The scanning electron microscope (SEM) and transmission electron microscope (TEM) are powerful methods for the nanoscale characterization of materials and can be applied to aerosol particles. To gain the most from these tools, it is necessary to understand uncertainties in the measurement process and allow for errors during the data capture and analysis stages. Replicated measurements and statistical analyses enable consideration of repeatability and reproducibility issues and give precision to the measurements. Addressing accuracy issues is more problematic because some of the errors are systematic and non-statistical in nature, and in almost all cases the true value of the measurand is unknown.[1]

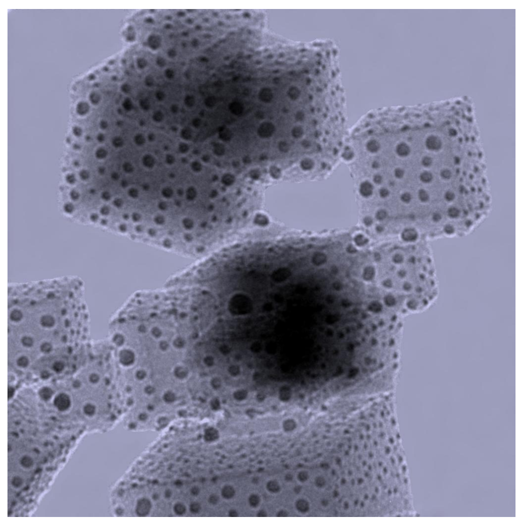


Image of cubes of magnesium oxide using 3-dimensional (3-D) chemical imaging methods and a scanning transmission electron microscope. Photo: NIST, J.H. Scott, J. Bonevich.

An overview of some of the measurement tools and methods used to characterize the chemical and dimensional properties of aerosols is shown in Table 2.1. Today these measurements are used for research studies, to provide input to climate models, and for various monitoring purposes (e.g., regional air quality, climate trends). There are a number of efforts ongoing to characterize and study aerosols within the context of climate. These involve developing capabilities for a range of applications from basic science to field measurement. The emphasis in most cases is a combination of atmospheric science, fundamental chemistry, and aerosol chemistry.

[1] Accuracy issues in chemical and dimensional metrology in the SEM and TEM, John Henry Scott, http://iopscience.iop.org/0957-0233/18/9/003; http://www.nrc-cnrc.gc.ca/eng/programs/inms/chemical-metrology.html

Table 2.1. Selected Tools and Instrumentation for Chemical and Dimensional Metrology for Aerosols	
Characterization Methods by Instrument/Type[2,3]	
Sealed Wave Channel	While common use is for physical oceanography and fluid mechanics studies, the wave channel can be modified by adding a sealed atmospheric chamber to enable measurements of aerosol composition and microphysics, trace gas and heterogeneous chemistry, and wave-induced bubble bursting
Aerosol Time of Flight Mass Spectrometer (ATOFMS)	This instrument is capable of measuring the size, density, optical properties, and chemical composition of single aerosol particles in real time, simultaneously; used extensively in both laboratory and field experiments for 15 years; provides data on the mixing state of airborne particulate matter
Chemical Ionization of Flight Mass Spectrometer (CI-TOFMS)	Now used to understand the behavior of key gaseous compounds in a simulated marine environment and relevant gas-particle interactions in the atmosphere
Fourier Transform Infrared (FT-IR) Spectroscopy of Aerosol Particles	Offline FT-IR spectroscopy offers capability for detailed characterization of the chemical composition and magnitude of organic fractions in sea spray under a range of different meteorological and oceanic conditions
Computational Methods for Modeling Heterogeneous Chemistry	New methodologies for modeling heterogeneous physicochemical processes on aerosol particles are being developed and implemented in the AMBER[4] suites of programs for molecular dynamics simulations; treatment of molecular motion at the quantum-mechanical level is combined with the underlying multidimensional potential energy surface
Condensation Particle Counters	Measures total particle number concentrations for particles larger than 3 nanometers (nm)
Particle Size Distribution	Optical particle counters measure particle size distributions in the size range from 0.1 µm to 3 nm with selectable size-bin ranges (e.g., Passive Cavity Aerosol Spectrometer Probe); differential electrical mobility analyzer systems size particle concentrations in the range from 3 nm to 1 µm (e.g., Scanning Mobility Particle Sizing System, Electrostatic Classifier)
Particle Chemical Composition	Semi-continuous bulk organic carbon (OC)/elemental carbon (EC) composition (Sunset Laboratory OC/EC Analyzer); real-time single particle composition of major inorganic (sulfate, nitrate, ammonium) and some organic species (Aerodyne Aerosol Mass Spectrometer); time-resolved aerosol collector (TRAC) for post-analysis of particle composition (PNNL-built)
SEM/TEM/ESEM	Both the scanning electron microscope (SEM) and transmission electron microscope (TEM) are powerful methods for the nanoscale characterization of materials. Environmental scanning electron microscope (ESEM) can analyze wet, uncoated samples in a low-pressure gaseous environment

[2] http://caice.ucsd.edu/Research_Tools.html
[3] http://www.pnl.gov/atmospheric/programs/aerosol.stm
[4] Assisted Model Building with Energy Refinement. http://ambermd.org/

Table 2.2 illustrates some of these efforts and the type of methodologies being employed.

Table 2.2.
Selected Ongoing Efforts in Chemical/Dimensional Metrology for Aerosols

Organization	Measurement Focus
Aerosol Chemistry and Climate Institute[5]	• R&D bridging the fields of atmospheric science and fundamental molecular science and chemistry; partnership between the U.S. Department of Energy's Pacific Northwest National Laboratory and the University of California at San Diego
The Center for Aerosol Impacts on Climate and the Environment (CAICE)	• Understanding heterogeneous chemical processes at a level that allows predictions to be made on atmospheric chemistry and climate; developing new approaches to perform fundamental studies in a controlled manner on complex multiphase chemical systems located at the University of California San Diego, is a Phase I Center for Chemical Innovation funded by the National Science Foundation
National Oceanic and Atmospheric Administration (NOAA), Earth System Research Laboratory (ESRL), Chemical Sciences Division[6]	• Measurement methods for aerosol optical and chemical properties; airborne field studies to characterize the "real world' aerosol properties and sources; and remote-sensing measurements of aerosols using both ground-based and airborne platforms; development of aerosol-cloud models; and model evaluation
World Meteorological Organization (WMO)[7]	• Global Atmospheric Watch (GAW) stations conducting aerosol chemical size and distribution measurements for multiple purposes: long-term trending, assessing impact of aerosols on regional and global climate, monitoring regional air quality, improving aerosol chemical transport models used in air quality forecast and climate models
Aerodyne Research	• Instruments for real-time and near real-time quantification of fine particulate matter necessary to understand climate impacts; developing instruments to quantify major inorganic components (SO_4, NO_3, Cl, NH_4); quantifying a general chemical characterization of organic fractions; development of less expensive, automated instruments for routine monitoring
Arizona State University	• Studies of the nature of aerosol particles such as airborne minerals, soot, and other small grains, their chemical and physical reactions (e.g., deliquescence, efflorescence) in the atmosphere, and their effects on air quality and climate change, using high-resolution transmission electron microscopy (HRTEM)

Vision

Chemical/dimensional metrology for aerosols will involve developing reliable methodologies for inorganic and organic trace analysis with emphasis on environmental applications, development of new types of analytical instrumentation for potential commercialization, and provision of certified reference materials to verify procedures for the determination of inorganic and organic contaminants in environmental samples.

Chemical/dimensional metrology for climate is working towards predictions that are accurate and serve as a solid foundation for future climate efforts. A critical component of the vision is chemical analysis tools

[5] http://www.pnl.gov/atmospheric/programs/acci/
[6] http://www.esrl.noaa.gov/research/themes/aerosols/aerosols.html
[7] http://www.wmo.int/pages/prog/arep/gaw/aerosol.html

that provide enough certainty to reliably understand the impacts of climate change mitigation. These tools will increase the understanding of key issues, such as "good" aerosols (e.g., for cooling or geo-engineering) or the link between gases and aerosols. The tools will allow insight beyond characterization of organic aerosols to understanding how aerosol particles change over time (e.g., hygroscopic changes). Changes can be effected in the models to reflect the newly acquired knowledge and produce predictions that approach field measurements.

Ideally, environmental microscopy would encompass the analysis of particle size, shape, and composition at the atomic and molecular level. Distinctions between the properties of black carbon, brown carbon, char, soot, and other important particles would be readily ascertained. *In situ* aerosol/cloud interaction processes would be precisely and accurately measured. Information would be shared through a global aerosol microphysics network where particle characteristics could be measured online.

Elements of the envisioned future for chemical/dimensional metrology are described in Table 2.3.

Table 2.3. Chemical/Dimensional Metrology Vision Elements		**Votes**
Methods	• Develop one instrument that characterizes integrated size, shape, composition of fine particles (e.g., mass mobility) *in situ*, in real time, and size resolved	●●●●●
	• Develop methods for differentiating between black carbon (BC), brown carbon, (BrC), char, and soot; identifying the start and end of the chemical continuum; differentiating between liquids and gas; reliably looking at BrC and separating it into possible components; ensuring BC properties and quantities are clearly defined and directly measured; and exploring other definitions beyond absorption in lower wavelengths	●●●●●
	• Measure aerosol/cloud interaction processes precisely and accurately *in situ*	●●●
	• Develop analytical techniques to characterize the chemical composition of aerosols at an atomic and molecular level	●
	• Develop statistical experiment design techniques to scale-up nm scale measurements to kilometer (km) scale properties	●
Instruments	• Support transmission electron microscopy (TEM) mass spectrometer instruments along with automated TEM stage for particle analyses	●●●●●
	• Develop global aerosol microphysics network (probes for chemical and optical properties) to enable inexpensive access to optical properties	●●●
	• Develop online measurement of particle shape	●●●
	• Support advances in environmental microscopy with atomic or near-atomic resolution to study chemical transformations on particle surfaces	●●
	• Automate particle energy dispersive spectroscopy (EDS) measurement and sizing using high resolution microscopes	●
	• Measure smoke emission source strength and properties directly over wildfires using unmanned aircrafts and suitable small, accurate instrumentation	●
	• Develop metrology across the ultraviolet (UV)/visible spectrum of particle shapes, including biological-origin particle (e.g., plant scrapings, viruses, bacteria, and spores)	

Table 2.3. Chemical/Dimensional Metrology Vision Elements		Votes
Standards & Protocols	• Develop an absorbing carbon standard that is readily processed, robust, and transferrable	●●●●●●●●
	• Support standard reference materials and methods for concentration composition (building on current NIST developments)	●●●●●●
	• Create size standards across measurement methods such as optical, geometric, and operational	●●●
	• Establish well-defined basic global terminology/nomenclature and definitions for optimal communication in the scientific community	●●●
	• Develop a “chemical mass standard” instrument to generate aerosol chemical standard of specific mass/size	●●
	• Establish standards for imaging soot structure inside a droplet	●
	• Establish fungal spore standards (bioaerosols)	●
	• Standardize methods to relate satellite aerosol optical measurements (e.g., aerosol optical depth [AOD]) to *in situ* measurement, such as mass, particulate matter (PM) 2.5/10, or size distribution	●
Data	• Compare methods for aerosol, soil, sediment, and water measurement techniques	●●●●
	• Understand the series of reactions leading up to formation of secondary organic aerosols (SOA), the chemical composition of SOAs, and the mechanisms for creation of new atmospheric particles (gas-to-particles conversion)	●●
	• Establish better understanding of uptake via flux with “real” measurements and a detailed source inventory of composition and size resolved surface flux measurements of fine particle matter (speciated) network	●●
	• Establish data to distinguish organic/carbonaceous components versus composition	●
	• Create accessible online data, such as the index of refraction	
Other Elements	• Understand how the aerosol phase affects chemistry and the ability to measure (e.g., liquid, solid, amorphous)	●●●
	• Understand gas particle distribution	●
	• Develop a molecular-level understanding of nucleation from the gas phase (birth and growth of particle)	●
	• Enhance knowledge of particle oxidation, which occurs quickly, including the oxidation potential and concentration needed to oxidize	

Challenges and Barriers

Aerosol metrology for climate faces numerous challenges. One overarching challenging is the difficulty of working in the Earth's atmosphere. In complex, natural systems it is difficult to identify with certainty the key parameters that must be measured to evaluate climate impacts. For chemical/dimensional metrology in particular, attaining the vision for metrology described previously will require overcoming some significant challenges. Underlying problems exist, such as a lack of central information, basic global terminology and definitions, and instrumentation for generating aerosol chemical standards. Addressing these challenges will take resources, time, and skilled personnel.

The infrastructure for addressing these challenges also needs improvement, particularly in the availability of consistently reported international trend and baseline data, global measurement networks, and ready access to instrumentation and test equipment.

Table 2.4 lists the major challenges and barriers facing chemical/dimensional metrology for climate.

Table 2.4. Chemical/Dimensional Metrology Challenges and Barriers		Votes
Instruments	• No single "aerosols community" exists for communication and cross-disciplinary collaboration; a central source for instrument standards, validation, and comparison is lacking	●●●●●
	• Working in the atmosphere—large (25 billion cubic km), heterogeneous, and dynamic—is challenging and a huge sampling problem – Appropriate tools are lacking (fast response ground sensors, remote LIDAR, millions of cheap sensors) – Even with tools it is uncertain whether the questions on climate impacts can be answered – The key parameters to be measured in the atmosphere's complex natural system are still uncertain	●●
	• Some tools will require long-term research (e.g., seven years to actual field use)	
Data	• Long-term trend and baseline data (high quality, climate-focused, often updated) with spatial and time components are lacking, particularly dynamic emission inventories for area sources	
	• Global measurement networks and a global, standardized database of measurements do not exist	
Other Barriers	• The need for investment in aerosols metrology is not well-understood; the result is a lack of strong drivers for research and development and sustained funding	●
	• Concerted effort to understand and address unintended consequences is lacking (e.g., consequences of removing controls on black carbon or other types of particles)	
	• Complex, multi-disciplinary research may be required; the pipeline of trained personnel is not robust, and the skill sets are not easily assembled	

Solutions and Approaches

Participants selected four priority areas to address, which are summarized below. More detailed pathways to success for each area are provided in Figures 2.1 through 2.4 on the following pages.

- **Large-scale aerosol instrumentation calibration, validation and comparison** (see Figure 2.1). Aerosol instrumentation requires calibration with dynamic aerosol standard sources. Such a standard source would produce an aerosol stream flow with controlled gas phase composition and known particle and droplet size and composition. An aerosol instrumentation calibration facility is needed to enable users to periodically calibrate individual instruments and to house instrument inter-comparison and cross-validation results.
- **Harmonized definitions and characteristics of black carbon, brown carbon, and soot for climate studies** (see Figure 2.2). Multiple definitions of soot and black carbon preclude effective data inter-comparison of these species. A lack of standards precludes effective instrument calibration and data archiving; different methods will require standards with a wide range of properties.
- **Automated Transmission Electron Microscope for micro-physical properties of aerosols** (see Figure 2.3). TEM automation will enable the measurement of the micro-physical characteristics of aerosols. These measurements would provide fundamental information on statistically significant numbers of particles, data which is currently difficult or impossible to obtain. Instrumentation and software will need to be developed to enable automation.
- **Reconciliation of atmospheric (top-down) and ground-based (bottom-up) emissions data** (see Figure 2.4). Reconciling top-down and bottom-up data is hampered by the lack of accurate emissions data, at the source and for vertical distributions, as well as the differences in spatial and temporal resolutions between ground and space *in situ* data. Reconciliation of this data would expand scientific understanding of the global carbon balance.

Figure 2.1.

Chemical/Dimensional Metrology Priority Topic:
Large-scale Aerosol Instrumentation Calibration, Validation, and Comparison

Measurement Challenge/Barrier

Aerosol instrumentation requires calibration with dynamic aerosol standard sources. Such a standard source would produce an aerosol stream flow with controlled gas phase composition and known particle and droplet size and composition. An aerosol instrumentation calibration facility is needed to enable users to periodically calibrate individual instruments and to house instrument inter-comparison and cross-validation results.

Actions and Approach

- Develop generation methods for aerosol particle flows of known particle size (1nm to 10,000 nm), chemical composition, and mass loading.
- Control carrier gas composition, including relative humidity and trace gas composition.
- Understand particle/droplet composition to include characteristic atmospheric aerosol components: sulfate, nitrate, chloride, ammonium, sea salt, and a wide range of organic species, soot, and major mineral dust.
- Develop capabilities to produce crystalline and amorphous solid particles of known shape and morphology.
- Develop capabilities to produce solid and liquid particles with known surface composition.

Performance Targets/Goals

- An aerosol instrument calibration facility supporting the broad aerosol science community (government, academia, private sector labs, instruments development programs, and commercial instrument calibration needs).
- A new generation of dynamic aerosols standard sources.

Applications

Provide calibration services to:

- a wide range of climate oriented R&D and trend monitoring activities
- aerosol PM health impact and exposure studies
- new generations of commercial aerosol composition instruments

Potential Stakeholders and Roles

Government

Metrology laboratories: aerosol instrument calibration facility.

Basic science, aerospace, environment and ocean: improved accuracy and precision for climate research.

Environment/regulatory: improved speciated/size resolved measurements of ambient particulates affecting human health, and better calibration of instruments used to control health/human exposure studies.

Industry

Instrument companies: ability to calibrate new generations of aerosol measurement instrumentation.

Impacts

- Significantly improves data on atmospheric aerosol particulate matter composition and mass loading.
- Enables ability to accurately inter-compare performance for a wide range of both research grade and routine monitoring instruments.
- Contributes to U.S. and international agencies active in U.S. research programs.

Milestones

2011-2012

- Develop an initial white paper specifying phase I capabilities for aerosol calibration facility.
- Develop specifications for initial range of dynamic calibration standard system.

2015

- Create and staff facility, host instrument, inter-comparison/ calibration studies for several aerosol types.

2020

- Continue to refine and expand facility as needed.

Figure 2.2.

Chemical/Dimensional Metrology Priority Topic:

Harmonized Definitions and Characteristics of Black Carbon, Brown Carbon, and Soot for Climate Studies

Measurement Challenge/Barrier

Multiple definitions of soot and black carbon preclude effective data inter-comparison of these species. A lack of standards precludes effective instrument calibration and data archiving; different methods will require standards with a wide range of properties.

Actions and Approach

- Set up a committee similar to the international Union of Pure and Applied Chemistry (IUPAC) to define carbon-based particulate matter terms for standards; focus on black and brown carbon and soot; consider other species.
- Develop standard dispersion methods for the relevant aerosols.
- Develop a synthetic approach to make reproducible materials.
- Coordinate across professional communities.
- Assemble a panel to assess needs for standards: who should develop materials, compositions, and techniques.
- Establish test capability for instrumentation calibration/inter-comparison for species of interest.

Potential Stakeholders and Roles

Government	**Metrology laboratories:** standards and reference materials.
Research Groups	**Science organizations:** Aerosol and black carbon-geosphere (soils, sediments) communities to conduct research.
Industry	**Instrument manufacturers:** test instruments and provide data.

Performance Targets/Goals

- A suite of particle standards to address a range of user goals.
- Goals for standards:
  - Stable, transferable, usable
  - Known size, shelf-life, surface composition and charge
  - Optical properties (extinction, scattering, albedo, index) for organic carbon (OC) and elemental carbon (EC)

Applications

- Instrument calibration for black and brown carbon and soot
- Reduction of uncertainties for these species
- Instrument comparisons

Impacts

- Grows scientific knowledge by reducing uncertainties in measurements.
- Increases confidence in climate change models.
- Provides consistent standards for studying particulate species that are currently poorly-characterized.

Milestones

2011-2012
- Assemble committee on standards
- Establish specific requirements for standards

2015
- Prepare and characterize standards
- Establish test capability to calibrate instruments for these species

2020
- Continue to refine and expand capability.

——— Support inter-comparisons ———→

Figure 2.3.

Chemical/Dimensional Metrology Priority Topic:
Automated Transmission Electron Microscope for Micro-physical Properties of Aerosols

Measurement Challenge/Barrier

TEM automation will enable the measurement of the micro-physical characteristics of aerosols. These measurements would provide fundamental information on statistically significant numbers of particles, data which is currently difficult or impossible to obtain. Instrumentation and software will need to be developed to enable automation.

Actions and Approach

- Develop capability for 3-D stage (xyz) manipulation on the TEM; the stage must be automated for detection and measurement to be accomplished.
- Collect energy dispersive X-ray spectroscopy (EDX) X-rays and diffraction data on individual particles.
- Collect digital images and develop data storage capabilities.
- Develop hierarchy for categorization of measurements.

Performance Targets/Goals

- Automated TEM xyz stage and automated 3D imaging capabilities.
- Organized hierarchy of measurements in standardized categories.
- A particle property inventory that is readily accessible.

Applications

- Aerosol studies (climate, health, and safety)
- Emissions source apportionment
- Compliance testing for emissions quantification and verification

Potential Stakeholders and Roles

Government **National Laboratories** **Academia** **Research Groups**	All stakeholder groups interested in atmospheric aerosols and climate models

Impacts

- Promotes health and safety through better characterization of aerosols.
- Provides fundamental information about the characteristics of statistically significant numbers of particles in a time-efficient manner.
- Supports protection of environment and climate.

Milestones

2011-2012
- Develop automated xyz stage

2015
- Develop automated 3-D imaging

2020
- Organize and bin measurements into sets of standard categories (i.e., shape, chemistry, other factors)

Figure 2.4.

Chemical/Dimensional Metrology Priority Topic:
Reconciliation of Atmospheric (top-down) and Ground-based (bottom-up) Emissions Data

Measurement Challenge/Barrier

Reconciling top-down and bottom-up data is hampered by the lack of accurate emissions data, at the source and for vertical distributions, as well as the differences in spatial and temporal resolutions between ground and space *in situ* data. Reconciliation of this data would expand scientific understanding of the global carbon balance.

Actions and Approach

- Explore pathways to ensure diverse agency representation for integration at the scientific level.
- Pursue application of standard measurements for compatibility and comparability across various inventories and data uses.
- Establish a prioritized work plan for harmonization of data.
- Integrate efforts with the Intergovernmental Panel on Climate Change (IPCC) to assure scientific coherence and accountability.

Performance Targets/Goals

- Scientific advancement in understanding of the global carbon balance.
- Standardization in measurements and adaptation to different communities.
- Reconciliation of top-down/bottom-up *in situ* data.
- Integration of science and data with policies and stakeholders.

Applications

- Regulations
- Emission controls
- Energy efficiency
- Renewable energy
- Forecasting emissions profiles
- Education and public outreach
- Economic planning

Potential Stakeholders and Roles

Government

- **Metrology laboratories:** Definitions, terminology, standardization, instrumentation, calibration, accuracies.
- **Environmental/regulatory:** Atmospheric—spatial coverage, link between space and time, aircraft and satellite instruments, vertical profiles, fluxes, transport. Ground-based—continuous localized emissions temporally resolved; emissions inventories, forecasting, regulatory issues.
- **Aerospace:** Space- and air-borne measurements; close data gap; global climate modeling
- **Energy:** Energy use and emissions estimates and impacts and projections; policies.
- **Forestry and agriculture**: Land-use changes, biomass burning, fuels, seasonality.

International

- **IPCC:** Robust scientific reference frame

Industry

- Translating knowledge to technology

Impacts

- Supports protection of environment and understanding of climate change.
- Grows scientific knowledge of climate impacts.
- Promotes health and safety via better science.
- Accelerates competiveness through more accurate baselines for industrial emissions.

Milestones

2011-2012

- Standardize and develop methods
- Organize stakeholder committee
- Asses current metrology understanding/standards
- Identify short- and long-term goals

2015

- Coordinate measurements from ground/*in situ*/space, and modeling
- Compare-understand-evaluate-validate-standardize-establish integration approaches for consistency

2020

- Fine-tune harmonized measurement techniques and integration
- Compare measurements and constrain models
- Reevaluate knowledge gaps and model requirements
- Reiterate processes, validate models, reevaluate standards

2025+

- Extend standardized measurements globally
- Stabilize all processes
- Develop climatologies and trends
- Inform stakeholders and public of findings

Photo courtesy of NASA, New Zealand GeoNet.

3. Optical Properties

Aerosols in the atmosphere are measured usually either by mass concentration or by optical schemes.[8] Atmospheric aerosols show large variations in their optical properties based on a number of factors including size, chemical makeup, shape, and other characteristics. These variations, combined with an incomplete understanding of how aerosols evolve in the atmosphere, create significant uncertainties in how global aerosol loading effects climate change. To address these shortcomings, existing optical capabilities will need to be augmented and new optical measurement methods and technologies will need to be developed and exploited.

Aerosols possess important optical properties such as scattering and absorption, which dictate their interaction with incoming radiation from the sun. Understanding these aerosol optical properties is essential to a full understanding of radiative effects of emissions and aerosol forcing. The important aerosol optical properties needed to calculate radiative influences include aerosol scattering coefficient, absorption coefficient, and asymmetry parameter, as well as phase function and polarization. Size is also a very important single-particle optical property to measure, where size can refer to a number of quantities, including wet size, dry size, size at formation, and size at a specified formation. The uncertainties in measuring these individual input parameters results in a substantial overall uncertainty in the context of forcing over a time period.[9]

State of the Art

Currently, most information to measure quantities (e.g., extinction, scattering, or absorption), comes from measurements of mass.[10] Optic properties are then inferred from *in situ* laboratory measurement results or field studies. These measurements currently result in uncertainties of 1% to 10% for extinction, 3% to 10% for scattering, and 5% to 50% for absorption. Methods to measure aerosol extinction include cavity ring-down spectroscopy, extinction cells, or cavity attenuated phase shift spectroscopy techniques. Scattering is measured through nephelometers or integrating spheres, while absorption can be measured using filter-based or photo-acoustic spectroscopy.

Aerosol optical depth (AOD) is another important optical property, which is one of several properties (including the light scattering coefficient) measured by the Global Atmosphere Watch (GAW) aerosol program. GAW aims "to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality up to multidecadal time scales." Since GAW measurements are made at surface-based stations, global climatologies (series of charts indicating the long-term average of atmospheric and oceanic conditions) are difficult without satellite measurements. However, correspondence with satellite measurements requires understanding of the column and precision AOD measurements. Furthermore, AOD measurements are difficult to understand without the aerosol profile.

More detailed information on the vertical aerosol distribution is measured by the GAW Atmospheric LIDAR (Light Detection and Ranging) Observation Network (GALION), which uses advanced laser remote sensing in a network of ground-based stations.[11] Multiple aerosol properties can be derived from light detection and ranging (LIDAR) measurements, including backscatter coefficient, extinction coefficient, and optical depth. These and other properties are determined through the use of multiple types of LIDAR, including elastic LIDAR, (multi wavelength) Raman LIDAR, high spectral resolution LIDAR

[8] http://downloads.climatescience.gov/sap/sap2-3/sap2-3-final-report-all.pdf
[9] Stephen E. Schwartz, *Variation of Aerosol Optical Properties and Radiative Implications*, Aerosol Metrology for Climate Workshop, March 14-15, 2011.
[10] Dan Lack, *Measurement Needs and Challenges for Absorbing Aerosol*, Aerosol Metrology for Climate Workshop, March 14-15, 2011.
[11] http://www.wmo.int/pages/prog/arep/gaw/aerosol.html

(HSRL) and the state-of-the-art LIDAR systems that measure multiple quantities simultaneously. GALION, however, still leaves researchers with multiple unanswered questions. There is uncertainty in the precision of the GALION-measured extinction profiles. It is unclear if extinction climatology can be derived and made into a climate record. In addition, it is also unclear how to validate the retrieved microphysical values of real index of refraction (n_r), imaginary index of refraction (n_i), droplet concentration with a given radii.[12]

There are several areas of research and technology development that could aid in the measurement of optical properties. This research includes source and detector characterization, calibration on polarimetry channels, validation of the inverse methods in LIDAR and the calibrations for fixed magnitude star-observing experiments. In addition, new technology development is needed, including new sources, detectors, filters, and notch filters. In general, instrumentation needs to become smaller and less expensive to allow for the use of a wide range of instruments spaced geographically and temporally, which cannot be achieved with current expensive instrumentation.

Vision

A number of advances in measurement techniques, instruments, and standards are needed in order to allow for more useful and advanced measurements of optical properties that include absorption, scattering, asymmetry, index of refraction, extinction, and polarization. In the area of measurement techniques, the continued development of multiple measurement capabilities is expected to lead to great advances in the aerosols field. These capabilities include measurements of vertical distributions of optical properties, UV to far-IR spectral measurements, real-time morphology, consistent size measurements using different techniques (e.g., optical or mobility techniques), and miniaturized and well-characterized aerosol measurement techniques that will allow for routine measurements utilizing transport means such as balloon-borne sounding system (sondes). In the area of standards, the community envisions an aerosol calibration facility for both optical and morphological measurements in addition to absorbing aerosol standards. In terms of instruments, it is envisioned that smaller, miniaturized instrumentation will lead to routine measurements of aerosol vertical distributions, extinction, scattering, and other important optical properties. In addition, optical means of determining particle shape and morphology and the development of a multi-wavelength, high spectral resolution LIDAR for the measurement of aerosol vertical distributions are also important aspects envisioned.

[12] Raymond Hoff, *Optical Properties: The Global Atmosphere Watch (GAW) Aerosol LIDAR Observation Network (GALION): Issues Involved with Obtaining Precise Optical Extinction Profiles for Climate Records*, Aerosol Metrology for Climate Workshop, March 14-15, 2011.

Elements of the envisioned future for optical properties are described in Table 3.1.

Table 3.1. Optical Properties Vision Elements

Methods	• Achieve consistent size measurements using multiple measurement techniques (e.g., optical techniques, mobility techniques, etc.) (five years) – Measurements of diameter depends on community measurements—geometric diameter versus mobility diameter versus aerodynamic diameter
	• Augment collaboration of theorists and experimentalists to arrive at a more complete understanding of climate change (five years) – AEROCOM-project[13] model of collaboration (AEROCOM – aerosol comparisons between observations and models)
	• Improve understanding of whether micro-physics and nanoscale properties translates to macroscopic predictability of forcing (a macroscopic property) (10 years)
Instruments	• Develop multi-wavelength, high spectral resolution LIDAR for measurement of aerosol vertical distribution (five years)
	• Establish a method for relating light absorption by filter deposit to in-situ absorption (five years)
	• Develop inexpensive, well characterized, accurate, and precise absorption instruments – Global surface monitoring or vertical profiling (five years)
	• Develop optical determination of particle shape/morphology (five years)
	• Create portable, automated aerosol measurement units (10 years) – Solar-powered, self-contained, for optical total mass measurements
	• Develop routine measurement of aerosol vertical distribution (particle sensors, balloon sounding systems) (15 years) – Smaller, miniaturized instrumentation, potentially disposable, measure extinction, scattering (e.g., place on weather balloon platforms, sample twice daily across the world)
	• Measure asymmetry parameter, the fraction of light sent into the forward hemisphere. – Enable radiative forcing calculations
Standards/ Protocols	• Understand spectral consistency from UV to far-IR (five years)
	• Establish mono-disperse, absorbing, calibrated refractive index (across multiple wavelengths), aerosol standards (five years)
	• Establish aerosol calibration facility (optical and morphological) (five years) – Generate and characterize sizes, types, shapes of aerosols
	• Calibrate particle density and devices, e.g., "standardized soot" and other shapes (five years) – Measured in individual laboratories – For equipment-makers: equipment is only as precise as means of calibration—better standards are needed – Incorporate both particle and gas perspectives

[13] See http://dataipsl.ipsl.jussieu.fr/AEROCOM/

Table 3.1. Optical Properties Vision Elements	
	• Develop standards for calibrating non-filter methods (five years) – Extinction, scattering, absorption using gases and standard particles
	• Establish a sensitivity study (five years) for key optical properties
	• Formulate the ability to calibrate and measure large particles (five years) – Largely ignored, typically for particle diameters > 5 µm
	• Optimize and validate particle counting methods (10 years)

Data	• Establish spectral characterization of aerosol absorption (wavelength: 0.3 µm to 5 µm) by type (smoke, pollution, etc) (five years)
	  – Expand to regional United States (10 years)
	  – Expand to global (15 years)

	• Develop inter-comparison of calculations/theory/modeling for scattering and absorption of mixed particles, non-spherical particles with measurements; theory should match measurements (five years)
Important Properties to Measure	• Measure absorption coefficient, scattering coefficient, asymmetry parameter, and index of refraction

	• Address additional forcing needs:
	  – Altitude-dependent optical properties
	  – Extinction coefficients
	  – Wavelength-dependent optical properties

	• Understand polarization: full Mueller matrix
	• Establish reference standards for shortwave absorption by carbonaceous aerosol
	• Predict optical properties such as phase-function
	• Validate optical properties with laboratory results
	• Measure classes of particles morphologically; correlate morphological properties with optical properties

Challenges and Barriers

There are many technical challenges that must be addressed to improve the gathering of quantitative information from optical interrogation methods on aerosol particles; these advances should provide significantly more information about the physical and chemical properties of aerosol particles. Among the challenges, one of the most critical areas is the lack of a strong correlation between measurement data and simulation models—i.e., making models look realistic. Furthermore, optical aerosol measurement equipment has not followed the miniaturization and cost reduction pathways that have been observed by a number of other industries, such as mobile phones and health diagnostics. Other challenges include the lack of conversion relationships for different aerosol-type definitions, lack of simplified systems to calibrate instruments used to measure optical properties derived of aerosols, an inability to quantify the morphology of unique particles in analogy to the fractal aggregate concept, and an insufficient number of technically trained personnel/staff. An overview of the challenges identified for optical properties is given in Table 3.2.

Table 3.2. Optical Properties Challenges and Barriers		Votes
Instruments	• Instruments lack the miniaturization of devices such as cell phones. – Development of "lab-on-chip" for aerosol metrology, i.e., instruments on chip	●●●●●●●●
	• Equipment is expensive; basic cost reductions are needed	●●●●●●●●
Standards/ Protocols	• A strong linkage has not been established between measurements and simulations (e.g., definitions)	●●●●●●●●●
	• Conversion relationships are lacking for different definitions of the same properties. – Standardized terms and procedures in the form of a glossary are needed	●●●●●●●●
	• Standardized terminology is not available in Network Common Data Form (NetCDF) and Hierarchical Data Format (HDF); e.g., a term like "diameter" does not have a standard definition and often needs an additional qualifier	●●●●●●
Data	• Tools for measurements of mixed carbonaceous aerosols are lacking, including spatial coverage, evolution of coatings, and optical properties	●●●●●●
	• Quantitatively describing the features of unique aggregates is difficult or not possible	●●●●●
Infrastructure	• A standardized air calibration facility is not available	●●●●●●
	• An optical calibration facility (e.g., filters, sources, detectors) does not exist – Increased access and broad awareness of facility capabilities should be provided – Facility needs to be self-supporting based on demand	●●●
Other	• There is no clear national vision about the impacts of climate change	●●●●●●
	• A shortfall of technologically-trained personnel is anticipated by 2015; more education is needed	●●●●●●

Solutions and Approaches

Participants selected seven priority areas to address, which are summarized below. More detailed pathways to success for each area are provided in Figures 3-1 through 3-6 on the following pages.

- **Morphology Quantification for Unique Particles** (see Figure 3.1). The ability to quantify the morphology of unique particles and compare particle morphology is a fundamental need for all types of aerosol measurement. Some difficult types of particles requiring quantification include: fractals, non-spherical shapes, mixed particles, and particle combinations. This capability will allow a quantitative correlation of physical properties to morphological properties. Quantitative particle descriptions would help to standardize aerosol science and allow easy comparison of collected data.

- **Standardization of Data Formats** (see Figure 3.2). Currently, there is inadequate standardization of terminology in databases using Network Common Data Form (NetCDF) and Hierarchical Data Format (HDF) NetCDF. In order to address this barrier, data naming conventions of the aerosol science community needs to be coordinated with the climate and forecast (CF) metadata. NIST in particular could take the lead in this coordination.

Additional coordination is needed with the Hierarchical Data Format (HDF5) community. Modelers, in particular, will use the NetCDF data inputs.

- **Education and Training for Aerosol Measurement** (see Figure 3.3). There is a current need for more technical-trained personnel/staff in the area of aerosol measurement, optical methods or otherwise. Opportunities for increasing the number of aerosol scientists include implementing training programs on aerosol technology or encouraging scientists in a variety of other fields to concentrate on the issues in aerosol science. Increasing the number of investigators and integrating researchers from other disciplines would augment how data is collected and analyzed.

- **Affordable, Portable, Smaller-scale Instrumentation for Measuring Optical Properties** (see Figure 3.4). Reducing the size and cost of optical properties measurement instrumentation is needed to allow for its pervasive use across a number of existing platforms (commercial aircraft, ships, etc.). While various technologies have pursued aggressive miniaturization and cost reduction strategies—e.g., microchips, optical aerosol measurement equipment has not adhered to this type of progression. Instrumentation miniaturization will enable unobtrusive collection of significantly more data.

- **Effective Linkage between Measurements and Simulations** (see Figure 3.5). Increased communication and linkages between modelers and experimentalists is needed in order to create more precise models that better simulate real world conditions. These more precise models would ultimately enable forecasting climate forcing and other more complex climate processes. This increased communication should allow for basic parameters for models mapped out by experimentalists, as well as the co-validation of model parameters that can be measured in laboratories.

- **Standards and Methods for Calibration of Aerosol Photometers** (see Figure 3.6). Standards and methods for the calibration of aerosol photometers are needed in order to develop a simple system to calibrate instruments used to measure optical properties derived of aerosols. These properties can include absorption, scattering, or extinction as derived from morphology and indices. The end result can be a laboratory capability of producing well-characterized aerosols for the evaluation, validation, and performance calibration of sensing technologies.

Figure 3.1.

Optical Properties Priority Topic: Morphology Quantification for Unique Particles

Measurement Challenge/Barrier

The ability to quantify the morphology of unique particles and compare particle morphology is a fundamental need for all types of aerosol measurement. Particles requiring quantification that pose significant challenges include: fractals, non-spherical shapes, mixed particles, and particle combinations. Quantitative particle descriptions would allow correlation of physical and morphological properties and help to standardize aerosol science.

Actions and Approach

- Identify and begin to characterize unusual particle morphologies: fractals, non-spherical shapes, mixed particles, and combinations of these (e.g., fractals composed of non-spherical primary particles).
- Validate/develop conversion relationships between aerosol diameters from varied instruments.
- Quantify fractal, non-spherical, mixed state, and hybrid combinations.
- Explore quantities needed for different applications.
  - Fractal aggregates have fractal dimension, but recently it has been shown this is not sufficient for a full description; relevance of quantities will vary for various applications (e.g., scattering, absorption of light, mobility, etc.)

Performance Targets/Goals

- Useful, relevant quantitative descriptors for any particle morphology.
- Ability to compare any particle morphology to another quantitatively.
- Ability to correlate other physical properties to morphological properties, quantitatively.
- Unification of overall particle geometry, convexity.

Applications

- Quantitative particle morphology for aerosols
- Correlation of physical properties with morphology for a variety of particles
- Standardization of particle size definition and morphology

Potential Stakeholders and Roles

Government **International** **Standards Organizations** **National Laboratories** **Industry** **Private Research Groups** **Trade Groups** **Academia**	All stakeholders need quantitative descriptive abilities

Impacts

- Supports protection of environment and climate via expansion of scientific knowledge on unusual particles.
- Establishes broad systemic quantification capability for particle morphology.

Milestones

2011-2012
- Identify candidate particles and morphologies for characterization
- Begin to quantify morphologies

2015
- Complete development of known morphologies
- Develop methods for physical-morphology correlations

2020
- Identify new particles for characterization and continue to quantify

Figure 3.2.

Optical Properties Priority Topic: Standardization of Data Formats

Measurement Challenge/Barrier

Currently, there is inadequate standardization of terminology in databases using Network Common Data Form (NetCDF) and Hierarchical Data Format (HDF) NetCDF. To address this barrier, data-naming conventions of the aerosol science community need to be coordinated with climate and forecast metadata. In addition, strengthened conversion relationships for different aerosol and atmospheric science terms to enable a common vocabulary for physical properties.

Actions and Approach

- Develop multi-organization plan for coordinating the data naming conventions of aerosol science community with climate and forecast metadata. (http://cf-pcmdi.llnl.gov/governance)
- Convene researchers (theorists, experimentalists, and field) to agree on common usage of terms for conversion relationships.
- Coordinate with the HDF5, a well-known data model, library, and file format for storing and managing data. www.hdfgroup.org/HDF5
- Finalize conventions and gain consensus from diverse stakeholders and users.

Performance Targets/Goals

- Standardized naming conventions that will enable common usage of data.
- Interoperability with common data formats already in use by climate and forecasting groups.

Applications

- Modelers using NetCDF inputs
- Scientific studies on aerosols

Potential Stakeholders and Roles

Government	**Aerospace, environment and ocean, energy, science, metrology laboratories:** coordination and consensus on data-naming conventions
Academia	University Corporation for Atmospheric Research (UCAR)

Impacts

- Enables wider, more consistent and reliable use of data (less uncertainty of results as definitions are clear).
- Agreed-upon conventions that could be used globally in large databases.
- Better and more consistent inputs to climate models leading to more comparable model outputs.

Milestones

2011-2012

- Identify lead organization for reviewing and developing naming conventions

2015

- Complete data terminology activities; results vetted with user community

2020

- Common data terminology usage in large databases

Figure 3.3.

Optical Properties Priority Topic: Education and Training for Aerosol Measurement

Measurement Challenge/Barrier

There is a current need for more technically trained personnel in aerosol measurement, optical methods, and other areas. Increasing the number of investigators and integrating researchers from other disciplines would augment how effectively aerosols data is collected and analyzed.

Actions and Approach

- Motivate the transfer of the existing knowledge pool to other disciplines (e.g., a material science/chemical engineer could move to the aerosol science technology development area).
- Implement a training program on aerosol technology and operation of calibration facilities and equipment.

Performance Targets/Goals

- Increase/keep constant the number of R&D personnel in aerosol science.
- Established curricula in universities, and increased awareness of the need for scientists trained in the field.
- Established technical training programs.

Applications

- Workforce in aerosol science
- Aerosols research community
- Quantification and verification of greenhouse gas emissions

Potential Stakeholders and Roles

National Laboratories	Training programs, post-doctoral research
Academia	Curricula for undergraduate and graduate studies; programs in aerosol science
Industry	Training programs for instrumentation and calibration

Impacts

- Contributes to economy and jobs by providing high-skilled positions in aerosols science.
- Ensures continuing trained workforce for quantification of climate-related compounds.
- Supports continued research and scientific understanding of aerosols and impact on climate.

Milestones

2011-2012
- Initiate development of curricula and training programs
- Conduct industry-government-academia education/training

2015
- Continue implementation of training and education programs

2020
- Continue implementation of training and education programs

Figure 3.4.

Optical Properties Priority Topic:
Affordable, Portable, Smaller-Scale Instrumentation for Measuring Optical Properties

Measurement Challenge/Barrier

Reducing the size and cost of optical properties measurement instrumentation is needed to allow for its pervasive use across a number of existing platforms (commercial aircraft, ships, etc.). While various technologies have pursued aggressive miniaturization and cost reduction strategies (e.g., microchips), optical aerosol measurement equipment has not followed this progression.

Actions and Approach

- Design systems to maintain performance and cost requirements.
- Identify opportunities for applications (e.g., transportation carriers) and possible demonstrations.
- Minimize instrument electric power consumption (battery operated).
- Ensure non-intrusive nature of instrumentation products (low noise, minimized heat dissipation, small size).

Performance Targets/Goals

- Adequate tradeoff between cost and performance.
- Includes the following attributes: reduced size, rock mount, portable, balloon launch, radio-sonde capability.
- Utilization of platforms of opportunity (commercial aircraft, ships, etc.).

Applications

- Ambient air quality and exposure studies
- Long-term climate studies
- Occupational health and safety monitoring
- Commercial and medical applications

Potential Stakeholders and Roles

Government	Regulatory
National Laboratories	Standards and verification
Industry	Customers
Small Business	Innovations in instruments

Impacts

- Supports protection of environment and climate and promotes health and safety via greater access to key data on aerosols.
- Accelerates competiveness via new instrumentation and potential for export.
- Contributes to economy and jobs through new instruments and small business start-ups.

Milestones

2011-2012	2013	2015	2018	2020	2025+
• Create blueprint for instrument development	• Apply resources	• Conduct demonstrations and prototyping	• Seek and gain agreements with platform providers	• Achieve commercial production	• Evaluation of technology and impacts on data, baselines

Figure 3.5.

Optical Properties Priority Topic: Effective Linkage Between Measurements and Simulations

Measurement Challenge/Barrier

Increased communication and linkages between modelers and experimentalists is needed to create more precise models that better simulate real world conditions. This increased communication should allow basic parameters for models to be mapped out by experimentalists, as well as co-validation of model parameters that can be measured in laboratories.

Actions and Approach

- Ensure measurement providers have enough measurements and the right data for modelers; explore gaps and challenges.
- Map out basic parameters needed for models and correlate with experimentalists.
- Co-validate what modelers use with what can actually be measured in laboratories.

Performance Targets/Goals

- Creation of an optical data perspective that is globally applicable for climate studies, including identification of the optical properties that are most important.
- Increased collaboration between modelers and experimentalists.

Applications

- Forecast of climate forcing
- Modeling of greenhouse gas emissions

Potential Stakeholders and Roles

International	**AEROCOM**-project (international science initiative on aerosols and climate)
National Laboratories	Data and parameters for models
Private Research Groups/Associations	American Association of Aerosols Research (AAAR), American Geophysical Union (AGU)

Impacts

- Supports protection of environment and climate and promotes health and safety via more accurate models and simulations.
- Greater consistency between experiment and simulation.

Milestones

2011-2012
- Increase people and information exchange between AEROCOM, AAAR, and AGU
- Identify basic parameters

2015
- Co-validate data from experiments with model outputs

2020
- Add new models and experiments

Figure 3.6.

Optical Properties Priority Topic: Standards/Methods for Calibration of Aerosol Photometers

Measurement Challenge/Barrier

Standards and methods are needed to develop a simple system to calibrate instruments used to measure optical properties of aerosols. These properties can include absorption, scattering, or extinction coefficients as derived from morphology and indices.

Actions and Approach

Generate particles of interest:

- Particles: poly-styrene, gold, suspended silicon, soot, carbonized spheres
- Aerosolization: nebulizer, electrospray
- Spectrum: dyes, plasmatic structure
- Scattering: size and morphology

Conduct characterization studies of particles:

- Standard imaging technology particle counters
- Cavity ring down spectroscopy (CRDS)
- UV-visible spectroscopy
- Bulk material characterization
- Imaging Mie theory
- Aerosol types (i.e., glass bead, Arizona dust, Savannah smoke) tor instrument calibration

Performance Targets/Goals

- A laboratory capability of producing characterized aerosols for validity/evaluation and calibrating performance of sensing technologies.

Applications

- Calibration of field instruments
- Technology evaluation
- Re-evaluation of historical data-sets
- Reference data for particle classes

Potential Stakeholders and Roles

Government	Regulators
Industry	Instrument vendors
Academia	Atmospheric scientists

Impacts

- Supports protection of environment and climate and promotes health and safety via greater understanding of the science of aerosols.
- Provides simpler, more cost-effective, and standardized measurement of optical properties to provide consistency across studies and enable greater number of measurements.

Milestones

2011-2012

- Generate particles of many types
- Initiate characterization studies

2015

- Functional laboratory available to calibrate and test equipment

2020

- Continued refinement and improvement as needed

4. Modeling

Models of climate processes provide tools to quantitatively describe interactions between the atmosphere, land, and oceans. Models can range from simple estimations to complex simulations of various processes. Two critical components of models are the mathematical equations and input data, both which depend on accuracy to achieve realistic simulations. Models can be created to investigate a specific question, such as SOA and cloud interaction. Modeling depends on outputs from Optical Properties and Chemical/ Dimensional Metrology for both data inputs to the models and model validation via field measurements.

State of the Art

Modeling of aerosols usually falls into the more general category of climate models. These models use various methodologies, such as box models and radiative-convective models, to accurately model climate processes across all scales. Some general climate models currently in use include the National Aeronautics and Space Administration (NASA)/Goddard Institute for Space Studies (GISS) General Circulation Model (GCM), NOAA/Geophysical Fluid Dynamics Laboratory CM2 global climate mode, and NCAR/UCAR Community Climate System Model (CCSM), NCAR Whole Atmosphere Community Climate Model (WACCM). A recent report on aerosols and climate science from the U.S. Climate Change Science Program contains a good overview of measurement issues and the climate models currently in use.[14]

Aerosol interactions can be simulated with stand alone models or as components of larger scale climate models. Recent research at Pacific Northwest National Laboratory resulted in a cloud-resolving model embedded within each grid cell to account for small features such as aerosols. Aerosol effects on clouds, and vice versa, can be simulated using cloud and aerosol properties statistics from the reference material. Small features, such as aerosols, clouds, and pollution point sources, can greatly impact global climate. Improved modeling and understanding of these small features will improve predictions of climate change.

Vision

Participants identified a wide range of needs and visions for the future (see Table 4.1). Goals specifically applicable to measurement include:

- Expanded database of chemical physical properties of organics including refractive indices, solute activity co-efficient and water activity, and mass absorption co-efficient.
- Improved source emission characterization including, size distribution, standardization of black carbon measurements, particle morphology, and characterization of ambient aerosols and elemental carbon for modeling.
- Achieving better than 1% absolute radiometric calibration for on-orbit imagers.
- A global database of aerosol size distribution, shape, and mixing state for black carbon, elemental carbon, and organic carbon (including near source and ambient measurements).
- Achieving aerosol standards for climate change solutions by developing a suite of updated and relevant reference materials.

[14] http://www.climatescience.gov/Library/sap/sap2-3/final-report/default.htm

Table 4.1. Modeling Vision Elements	
Methods	• Accurately quantify BC in snow/ice measurement techniques
	• Achieve greater than 1% absolute radiometric calibration for space-based spectro-radiometerology/VIS (visible light at 400-700 nm)/IR (750 nm – 1 mm) imagers
	• Develop sensitivity analysis of aerosol characteristics that can make radio frequency (RF) of BC go from positive to negative
	• Quantify brown carbon mass absorption cross-sections
	• Understand the role of black carbon as ice nuclei
	• Develop secondary organic aerosols production theory – Volatility basis – Smog chamber studies
	• Develop high throughput particle analysis in three dimensions
Standards and Protocols	• Understand parametric uncertainty (constraining measurements, standardized tests)
	• Develop reference materials for organic carbon/elemental carbon sampling and analysis
	• Understand inter-comparisons for theoretical simulations
Data and Instruments	• Develop validated and transparent database for modeling
	• Establish global database of aerosol size distribution, shape and mixing state (chemistry), including surface and aircraft
	• Understand extent of variation in single scattering albedo as a function of the internal mixing state of aerosol type and spatial distribution of mixing phases
	• Measure spectral refractive indices of many individual organic chemicals (particularly UV/short visible)
	• Create *in-situ* networks for validation of satellite observations and models
	• Understand precision/source-based emission factors
	• Measure particle size, shape, and mixing state for a range of important aerosol sources—both near source and within a typical model grid space (e.g., 1 degree longitude x 1 degree latitude x 100 meters)
	• Establish a database of morphology (particle shape effect)
	• Use models for predictions—measure Henry's constants, activity coefficients of the many thousands of organic chemicals used in chemistry mechanisms
Reference Material	• Attain calibrated celestial sources for nighttime atmospheric data
	• Validate light detection and ranging (LIDAR) with *in situ* data
Other	• Measure size-resolved particle albedo in real time
	• Robustly assess the impact of human activities (sector by sector, activity by activity) on the atmosphere, climate, and the environment

Challenges and Barriers

The challenges outlined in Table 4.2 were identified as those most impeding progress toward the goals identified for modeling of aerosols for climate.

Table 4.2. Modeling Challenges and Barriers		Votes
Instruments	• Instrumentation for advanced measurements is lacking	●●●●
	• Technology for isolating black carbon in liquids is limited	●●●
Standards/ Protocols	• Uniformity is lacking in current measurements	●●●●●
	• There is little traceability of models in use today	●●●●
Data	• Improve dissemination of evaluated data for use in models	●●●●●●●
	• Satellite and sub-ordinal measurements are not well-integrated with models	●●●●●
	• The accuracy of archived BC records in snow, ice cores, and lake sediments and translation of deposited BC to historic ambient concentrations is low; there are also technical issues with isolating BC in liquid or soil matrix and uncertainties when reproducing ambient values	●●●●
	• International access, coverage, and remote data are all lacking	●●●
	• Other countries do not adequately share information and data	●●
Other	• Significant resources are required to overcome challenges	●●●●●●
	• Limitations exist in computations in finely grained models	●●●●●
	• There is a lack of prioritization and knowledge of the measurements and data that are needed to support climate programs	●●

Solutions and Approaches

Five priority areas were identified and are summarized below. More detailed pathways to success for each area are provided in Figures 4-1 through 4-5 on the following pages.

- **Expanded Database of Fundamental Chemical and Physical Properties of Organic Compounds** (see Figure 4.1). Understanding the properties of organics will require an expanded database of fundamental chemical and physical properties. The database should include refractive indices, solute activity coefficients and water activity, and mass absorption coefficients. Building this database will be a large task and should include wide involvement from the aerosol metrology community.

- **Expanded/Improved Source Emissions and Ambient Characterization** (see Figure 4.2). Achieving better source emissions and ambient location characterization requires new measurements, instruments, standards, and database development. Improved characterization should include, size distribution, standardization of BC measurements, particle morphology, and characterization of ambient aerosols and elemental carbon for modeling. The current tendency is to focus only on absorption in this area; emissions should have equal representation.

- **Improved Radiometric Calibration for On-Orbit Imagers** (see Figure 4.3). The problem of maintaining quality (greater than 1%) spectral radiometric calibration of imagers on orbit involves characterizing multiple pixels and understanding how they respond with clouds and scattered light—a highly complex scientific problem. Collaborative activities could accelerate progress in developing a calibrated hyper-spectral image projector that can record information on-orbit and last for 10–20 years.

- **Global Database of Aerosol Size Distribution, Shape, and Mixing State** (see Figure 4.4). A database is needed that focuses on black carbon, elemental carbon, and organic carbon (including near-source and ambient conditions). Developing the database will require identifying instruments, methods, quality assurance/quality control (QA/QC) issues, accuracy, precision, and uncertainty of current measurements and generating a uniform global database, with metadata and common format. This activity builds on the new capabilities developed under Modeling Priority Topic: Source Emissions and Ambient Characterization.

- **Reference Materials for Aerosols Relevant to Climate** (see Figure 4.5). A suite of updated and relevant reference materials for aerosols will provide the scientific community with access to a vital set of aerosol standards for climate change solutions. A greater number of measurements are needed as well as calibrated celestial sources for nighttime atmospheric data.

Figure 4.1.

Modeling Priority Topic:

Expanded Database of Fundamental Chemical and Physical Properties of Organic Aerosol Compounds

Measurement Challenge/Barrier

Understanding the properties of organics will require an expanded database of fundamental chemical and physical properties. The database should include refractive indices, solute activity coefficients and water activity, and mass absorption coefficients. Building this database will be a large task and should include wide involvement from the aerosol metrology community.

Actions and Approach

- Create a database for properties of organic compounds found or potentially found in organic aerosols.
- Organize physical properties, including refractive indices) and activity coefficients (e.g., water/solute).
- Organize chemical properties, including rate coefficients, gas, and aqueous; include other factors such as Henry's law constant, equilibrium constant/crystallization, deliquescence, and reference material.

Potential Stakeholders and Roles

Government	**Metrology laboratories:** Properties and database development
National Laboratories	Properties development
Academia	Properties development
Decision makers	Users of data

Performance Targets/Goals

- Better data organization structure and broad involvement of scientific community.
- Collection of existing data and determination of capabilities.
- Effective inputs to models and simulation tools.
- Large amount of accessible data on organic aerosols.

Applications

- Atmospheric and ground-based models to determine effect of aerosols on environment, climate, and health
- Understanding/allocating source emissions

Impacts

- Contributes to economy and jobs by creating a basis for economic decisions.
- Supports protection of environment and climate; provides basis for environmental decisions.
- Promotes health and safety via data to study health effects.
- Grows scientific knowledge via expanded basis for future scientific knowledge.

Milestones

2011-2012
- Organize community to collect and compare data

2015
- Validate data and optimized models

2020
- Improve and assimilate data

Figure 4.2.

Modeling Priority Topic:
Source Emissions and Ambient Characterization

Measurement Challenge/Barrier

Achieving better source emissions and ambient location characterization requires new measurements, instruments, standards, and database development. Improved characterization should include, size distribution, standardization of BC measurements, particle morphology, and characterization of ambient aerosols and elemental carbon for modeling. The current tendency is to focus only on absorption in this area; emissions should have equal representation.

Actions and Approach

- Establish inter-comparisons and performance of instrumentation, including reference materials and uncertainty assignments per instrument.
- Measure specific sources and ambient locations where data quantity is low or non-existent. Sources for example, include biomass (open, cook stoves); ambient locations could include remote sites (Eastern Arctic).
- Develop laboratory and field studies characterizing atmospheric processing of emissions and physical/chemical transformation of particles.
- Develop instrumentation for online particle morphology and mixing state.

Performance Targets/Goals

- New measurements for distribution, particle morphology, (all species), and mixing state.
- Standardized BC measurements—as mass concentration (carbon-based measurements), organic carbon (light-absorbing carbonaceous matter) and absorption/scattering.
- Emissions inventory database and ambient database of chemical BC/OC, and particle shape.
- Portable, low-cost field instrument for widespread measurement of particle shape and mixing state.

Applications

- Assessment of mitigation options for decision-makers
- Understanding of aerosols and climate, especially in remote locations

Potential Stakeholders and Roles

Government	**Metrology laboratories, environment and ocean, energy, and regulatory:** instruments, testing, database development, inter-comparisons
Academia	Extension of existing activities
International	**World Meteorological Organization (WMO) and Global Atmosphere Watch (GAW):** Participation in data comparisons, other activities

Impacts

- Supports protection of environment and climate and promotes health and safety via improved scientific knowledge.
- Accelerates competitiveness via better baseline information and understanding of mitigation options.

Milestones

2011-2012

- Develop and test Instrumentation for new measurements and inter-comparisons

2015

- Implement technology in field and emissions studies
- Meet deadline for carbon reductions according to the Intergovernmental Panel on Climate Change

2020

- Continue to refine methodologies based on results

Figure 4.3.

Modeling Priority Topic: Improved Radiometric Calibration for On-Orbit Imagers

Measurement Challenge/Barrier

The problem of maintaining quality (greater than 1%) spectral radiometric calibration of imagers on orbit involves characterizing multiple pixels and understanding how they respond with clouds and scattered light—a highly complex scientific problem. Collaborative activities could accelerate progress in developing a calibrated hyper-spectral image projector that can record information on-orbit and last for 10–20 years.

Actions and Approach

- Image a standard extended source from orbit.
- Develop a hyperspectral image projector for on-ground calibration and characterization.
- Develop sources for ground-based thermal vacuum calibrations.

Performance Targets/Goals

- Better than 1% absolute spectral radiometric calibration for UV, visible, near infrared spectroscopy, and possibly thermal infrared for on-orbit imagers.

Applications

- Improving applicability of quantitative space-based imagery for long-term climate studies and for accurate aerosol, surface, cloud, and resource remote sensing analyses

Potential Stakeholders and Roles

Government — **Aerospace, environment and ocean, defense, metrology laboratories:** agencies that build and fly space-based imagers; agencies producing calibration standards; remote observing and instrument users and makers; test and validation of instruments and methods

International — **World Meteorological Organization (WMO) and Global Atmosphere Watch (GAW):** collaboration and validation

Impacts

- Supports protection of environment and climate via improved scientific knowledge.
- Enhances credibility and accuracy of baseline atmospheric data.
- Promotes health and safety via better understanding of potential impacts.

Milestones

2011-2012

- Establish collaborative plan

2015

- Image standard extended source from orbit
- Develop hyper-spectral image projector for on-ground calibration

2020

- Develop sources for ground-based thermal calibrations

Figure 4.4.

Modeling Priority Topic:

Global Database of Aerosol Size Distribution, Shape, and Mixing State

Measurement Challenge/Barrier

A database is needed that focuses on black carbon, elemental carbon, and organic carbon (including near-source and ambient conditions). Developing the database will require identifying instruments, methods, QA/QC issues, accuracy, precision, and uncertainty of current measurements and generating a uniform global database, with metadata and common format. This activity builds on the new capabilities developed under Modeling Priority Topic: Source Emissions and Ambient Characterization.

Actions and Approach

- Create database of aerosol particle size, optical properties, chemical BC/OC, particle shape, and mixing state, building on existing databases at NASA, NOAA, DOE, and EPA.
- Achieve monthly or weekly averages of data.
- Implement particle surface measurements.
- Develop methods for estimating measurement uncertainty of aerosols data.
- Develop methods to process global, gridded data.

Potential Stakeholders and Roles

Government

Metrology laboratories: generate standard aerosols for analysis

Aerospace: satellite data sets, surface networks

Environment and ocean: climate relevant data sets form few locations, aircraft measurements

Environment/regulatory: select surface, remote and aircraft data sets PM 2.5/PM 10 date networks for the United States

Performance Targets/Goals

- Integrated, global, gridded aerosol data set for selected aerosol types.
- Accessible database of size, shape, and mixing state.

Applications

- Climate modeling
- Locating future measurements
- Satellite data validation

Impacts

- Accelerates competitiveness by facilitating data sharing.
- Promotes health and safety, protection of environment and climate, via expanded scientific knowledge.
- Provides consistent accessible data for international use.
- Provides new understanding of black and brown carbon and organic carbon aerosols.

Milestones

2011-2012
- Develop a detailed plan

2015
- Establish methods, identify data sets, identify gaps in data

2020
- Release first version of interpreted data sets of surface measurement for selected aerosol types

2025+
- Gridded data sets and vertical profiles

Figure 4.5.

Modeling Priority Topic: Reference Materials for Aerosols Relevant to Climate

Measurement Challenge/Barrier

A suite of updated and relevant reference materials for aerosols will provide the scientific community with access to a vital set of aerosol standards for climate change solutions. A greater number of measurements are needed as well as calibrated celestial sources for nighttime atmospheric data.

Actions and Approach

- Develop a suite of reference materials for instrument calibration to address source emissions and ambient aerosols.
  - Particles with known refractive index and size, mixed composition
  - Example: silver/gold—use internally mixed light-scattering natural dust with organics to address source emissions
- Develop calibrated celestial sources.

Performance Targets/Goals

- Improved measurement accuracy through relevant instrument calibration.
- Reconciliation of emission source measurements with ambient aerosols measurements.
- High precision measurements to assess availability and optical properties for relevant species and aged aerosols.

Applications

- Instrument calibration
- Aerosol climate studies
- Related studies (health, safety, environment)

Potential Stakeholders and Roles

Government	**Metrology laboratories:** reference materials **Environment/regulatory:** guidance for standards
International	**International Organization for Standardization(ISO):** standards
Standards Organizations	**American Society for Microbiology (ASM):** standards
National Laboratories Industry, Private Research Groups	Users of standards

Impacts

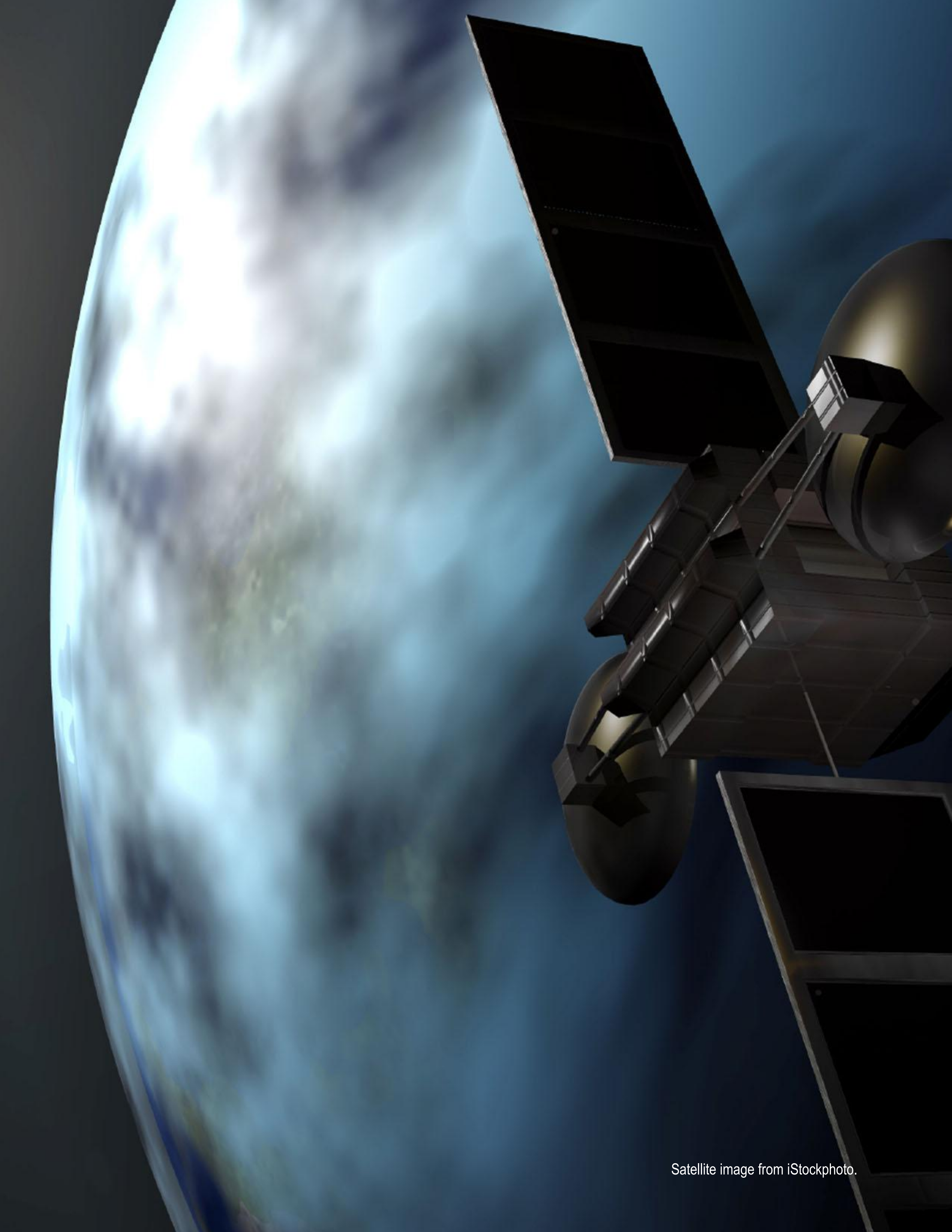
- Supports protection of environment and climate via expansion of scientific knowledge.
- Standardizes results to allow comparison across studies both domestically and globally.

Milestones

2011-2012
- Identify key reference materials needed
- Identify properties and applications
- Calibrate celestial sources

2015
- Complete development of reference materials and standards/protocols
- Develop capability for high precision measurements and calibration

2020
- Update and refine standards as needed



Satellite image from iStockphoto.

Collaborative Models

Existing Collaborations

A number of potential collaborative models were identified that could be effective in solving some of the problems in aerosol metrology.

- Hubs modeled after the Manhattan Project, and similar to those now underway at the U.S. Department of Energy (DOE) (http://science.energy.gov/bes/research/doe-energy-innovation-hubs/), and could include multiple agencies and organizations.
- Non-profit organizations like Fiatech (construction) and Sematech (electronics), where research could be cost-shared through member-pooled contributions, and would include a board of directors making decisions on research directions.
- Collaborations where efforts are centralized and focused, including the DOE Bioenergy Centers, DOE Advanced Research Projects Agency – Energy (ARPA-E), and Department of Defense (DOD), Defense Advanced Research Projects Agency (DARPA).

Collaborative Success Factors

Centralized, organized management of research has been a key factor for success in some collaborative activities, including the Hub model, ARPA-E and others. Overall this approach allows for greater leverage and coordination of resources among many different organizations with various objectives. This is particularly important for those collaborations where multi-disciplinary research is required.

Centralization of research management could provide a number of benefits:

- Collaboration on recruiting of critical communities and scientists would bring multi-disciplinary skills together.
- Providing a framework where many different communities involved can work under common goals and definitions would provide consistency.
- Definition of needs for community infrastructure, such as calibration facilities, tools, and data, would broadly increase capabilities for key measurements.

Mechanisms for Encouraging Collaboration

Many different communities are involved in aerosols metrology. As a result, research can often be stove-piped, which can inhibit collaboration.

Potential approaches for encouraging work among diverse disciplines and stakeholder communities include:

- A single facility with the capability to generate live aerosols is lacking and could be accessed widely for calibration. Such a facility could start at a minimum level and build capability and user communities over time. Initially it should consist of well-characterized aerosol size distribution and then build additional capability.

- One of the impediments to collaborating is distance. Virtual collaboration, which is cheap and easy to do, could include seminars and social media (e.g., similar to the NanoHub) to keep people involved. This would broaden the community at low cost.
- Greater interaction of modelers and researchers is needed. Modelers and lab researchers should interact more to understand the details of measurements and definitions (e.g., Aerocom for data collection).
- Many authorities on aerosol standards exist and there is a need to establish a common framework and legitimacy.
- This is a global community, and challenges need to be tackled at the international level, bringing together all stakeholders and communities.

Appendix A. Workshop Participants

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Michael Zachariah, National Institute of Standards and Technology

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Appendix B. Speaker Presentations

Peter Buseck, Arizona State University

Chemical/Dimensional Metrology: Identification and Analysis of Atmospheric Particles

Raymond Hoff, University of Maryland, Baltimore County (UMBC)

Optical Properties: The Global Atmosphere Watch (GAW) Aerosol Lidar Observation Network (GALION): Issues Involved with Obtaining Precise Optical Extinction Profiles for Climate Records

Mark Jacobson, Stanford University

Modeling: Incorporation of Aerosol Optical Properties into Climate Models

Ralph Kahn, National Aeronautics and Space Administration, Goddard Space Flight Center

From Measurement to Models: What Satellite and Sub-Orbital Instruments Can and Must Contribute

Dorothy Koch, United States Department of Energy

Programmatic Plenary: Uncertainties and Frontiers in Aerosols Research

Charles Kolb, Aerodyne Research, Inc.

Chemical/Dimension Metrology: Development of Advanced Field Measurement Techniques for Sampling Ambient Atmospheric Particles

Rao Kotamarthi, Argonne National Laboratory

Modeling: Aerosol Parameterizations and Evaluations using Observational Data

Daniel Lack, National Oceanic and Atmospheric Administration

Optical Properties: Challenges for In-Situ Measurements of Aerosol Absorption and Influence on Climate Forcing

Carrie Masiello, Rice University

Optical Properties: Elucidation of Environmental Carbon Cycles; Optical Properties: Elucidation of Environmental Carbon Cycles

Frank Raes, European Commission Joint Research Centre

Opening Plenary: The Role of Aerosols in Climate Change

Stephen Schwartz, Brookhaven National Laboratory

Optical Properties: Variation of Aerosol Optical Properties and Radiative Implications

Rodney J. Weber, Georgia Institute of Technology

Chemical/Dimension Metrology: How Physical and Chemical Properties Data Reflects Aerosol Formation Processes and their Evolution

Ping Yang, Texas A&M University

Optical Properties of Airborne Dust: The Effect of Particle's Nonsphericity on the Single-Scattering Properties and Downstream Applications


Photo courtesy of NASA.

Appendix C. References and Additional Resources

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