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Monitoring of aerosol forcing of climate from space: analysis of measurement requirements

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Abstract

We discuss the rationale for long-term monitoring of the global distribution of natural and anthropogenic aerosols (black carbon, sulfates, mineral aerosols, etc.) and clouds with specificity, accuracy, and coverage sufficient for a reliable quantification of the direct and indirect aerosol effects on climate, the anthropogenic component of these effects, and the long-term change of these effects caused by natural and anthropogenic factors. This discussion is followed by the formulation of specific scientific objectives of the Aerosol Polarimetry Sensor component of the National Aeronautics and Space Administration's Glory Project established within the framework of the US Climate Change Research Initiative.
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1. Introduction

Monitoring of global climate forcings and feedbacks, if sufficiently precise and long term, can provide a very strong constraint on interpretation of the observed temperature change and thereby influence environmental and energy policy decisions [1]. The considerable variability of observed temperature indicates that observations of climate forcings and feedbacks must be continued for decades. Since the

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climate system responds to the time integral of the forcing, a further requirement is that the observations be performed continuously. These two requirements make long-term satellite measurements the only practical means of monitoring the global change and its anthropogenically induced component provided that the measurements are sufficiently accurate [2].

Tropospheric aerosols play a crucial role in climate and can cause a climate forcing directly by absorbing and reflecting sunlight, thereby cooling or heating the atmosphere, and indirectly by modifying cloud properties [3–8]. The indirect aerosol effect may include increased cloud brightness, as aerosols lead to a larger number of smaller cloud droplets (the so-called Twomey effect [9]), and increased cloud cover, as smaller droplets inhibit rainfall and increase cloud lifetime [10]. Both forcings are poorly understood and may represent the largest source of uncertainty about future climate change [5–8].

Black carbon aerosols can contribute to global warming by absorbing the solar radiation and re-radiating the Sun's energy as infrared radiation that is trapped by the earth's atmosphere. Sulfate aerosols, produced from the sulfur dioxide gas that spews out of a volcano or from the burning of sulfur-bearing fossil fuels, reflect the solar radiation out into space and typically cause cooling. Aerosols, unlike greenhouse gases, have a short lifetime in the atmosphere. After they are produced they tend to mix with other agents, are transported within the troposphere both vertically and horizontally, and within about a week tend to disappear through sedimentation, rain out, etc. [4]. Because of both natural and anthropogenic events, aerosols are constantly being replenished and the anthropogenic aerosols, since the beginning of the industrial age, have been increasing. Aerosol can also play a critical role in precipitation but again some species of aerosols may increase precipitation, while others may inhibit precipitation. While it is recognized that aerosols play a key role, because of the uncertainty of the composition of the aerosols in the atmosphere, there remains great uncertainty in the effect that atmospheric aerosols have on climate and weather: hotter or cooler, more rain or less, etc.

Although several existing satellite instruments are used to study aerosols and their climatic effect on the global and regional scales [11–18], they remain rather limited in their ability to provide accurate particle characteristics other than the column optical thickness and an effective particle size. However, these parameters are not sufficient for an accurate evaluation of the direct effect and, especially, for long-term monitoring of changes in the direct effect caused by anthropogenic factors [2]. Furthermore, the completeness and accuracy of existing and planned measurements of aerosol and cloud parameters are not sufficient for reliable evaluation of the aerosol indirect effect and its regional variations [19,20].

In the framework of the US Climate Change Research Initiative (CCRI; http://www.climatescience.gov/about/ccri.htm) launched in June 2001 to study areas of uncertainty about global climate change, research on atmospheric concentrations and effects of aerosols is specifically identified as a top priority. One of the activities that the CCRI calls out to support this research is improving observations for model development and applications from observing systems. To that end, the National Aeronautics and Space Administration (NASA) plans to deploy a high-precision photopolarimeter called Aerosol Polarimetry Sensor (APS) that will help understand the climate-relevant chemical, microphysical, and optical properties and spatial and temporal distributions of human-caused and naturally occurring aerosols.

The main objective of this paper is to describe and justify *APS threshold science requirements*, which form the core of the APS project and are considered to be minimum requirements below which the utility of the APS project becomes questionable. It also lists *APS science goals*, which are defined as significant increments above the respective science requirements or as desirable additions to the set of minimum science requirements. Specific measurement and respective accuracy requirements will be detailed in Appendices A and B.

Table 1
Quantification of the direct aerosol effect

Required aerosol characteristics	Retrieved aerosol characteristics	
Spectral optical thickness $\tau_a(\lambda)$ Spectral single-scattering albedo $\varpi_a(\lambda)$ Spectral phase function $P_a(\Theta, \lambda)$ Chemical composition	Spectral optical thickness $\tau_a(\lambda)$ Effective radius $r_{eff,a}$ Effective variance $v_{eff,a}$ Spectral refractive index $m_a(\lambda)$ Nonsphericity $\varpi_a(\lambda)$	for two modes

In addition to these science objectives, the Glory APS will be used to provide proof of concept and risk reduction for a nearly identical instrument to be flown by the US National Polar-Orbiting Operational Environmental Satellite System (NPOESS) program (http://www.ipo.noaa.gov/Technology/aps_summary.html).

2. Direct aerosol effect

The left column of Table 1 lists aerosol parameters that are needed for a reliable quantification of the direct effect and its anthropogenic part [8,21,22]. All these quantities must be known in a wide range of wavelengths λ from the near-UV to the short-wave IR. The aerosol optical thickness is usually a direct product of applying a retrieval algorithm to satellite measurements, whereas the single-scattering albedo, the phase function, and the chemical composition can be determined or inferred provided that aerosol microphysical parameters such as the size distribution, spectral refractive index, and shape are retrieved.

The right column of Table 1 lists aerosol parameters that must be retrieved from space in order to determine the required aerosol characteristics: the spectral optical thickness, the effective radius and effective variance of the size distribution, the real and imaginary parts of the spectral refractive index, the shape, and the single-scattering albedo. Since the aerosol population is typically bimodal (see, e.g. [23]), all these parameters must be determined for each mode.

Note that the effective radius has the dimension of length and provides a measure of the average particle size, whereas the dimensionless effective variance characterizes the width of the size distribution, as follows [24]:

$$r_{\rm eff} = \frac{1}{\langle G\rangle}\int_{r_{\rm min}}^{r_{\rm max}} {\rm d}r\, n(r)\pi r^3, \tag{1}$$

$$v_{\rm eff} = \frac{1}{\langle G\rangle r_{\rm eff}^2}\int_{r_{\rm min}}^{r_{\rm max}} {\rm d}r\, n(r)(r - r_{\rm eff})^2\pi r^2, \tag{2}$$

where $n(r)\,{\rm d}r$ is the fraction of particles with radii from r to $r + {\rm d}r$ and

$$\langle G\rangle = \int_{r_{\rm min}}^{r_{\rm max}} {\rm d}r\, n(r)\pi r^2 \tag{3}$$

is the average area of the geometric projection per particle. It has been demonstrated [24] that different types of size distribution (power law, log normal, gamma, etc.) having the same values of the effective

Table 2
Quantification of the indirect aerosol effect

Required cloud and aerosol characteristics	Retrieved quantities
Cloud albedo $A_c(\lambda)$ Cloud particle effective radius $r_{eff,c}$ Cloud particle number concentration N_c Liquid water path	$\tau_c(\lambda)$ $r_{eff,c}$ $v_{eff,c}$
Aerosol particle number concentration N_a Aerosol particle effective radius $r_{eff,c}$ Aerosol chemical composition	$\tau_a(\lambda)$ $r_{eff,a}$ $v_{eff,a}$ $m_a(\lambda)$ shape for two modes

radius and effective variance possess similar scattering and absorption properties, thereby making r_{eff} and v_{eff} convenient universal characteristics of essentially any size distribution.

The corresponding APS minimum proposed measurement requirements listed in Appendix A include the retrieval of the total column optical thickness and average column values of the effective radius, effective variance, real part of the refractive index, and single-scattering albedo for each mode of a bimodal aerosol population. The optical thickness and the real part of the refractive index must be determined at multiple wavelengths in a wide spectral range, e.g., 0.35–2.5 μm. An integral part of the retrieval procedure must be the detection of nonspherical aerosols such as dust-like and soot particles. It has been demonstrated that, if ignored, nonsphericity can seriously affect the results of optical thickness, refractive index, and size retrievals [25–28].

3. Indirect effect

The aerosol effect on the cloud albedo can be detected and quantified from space by means of long-term global measurements of the change in the number concentration of aerosol particles acting as cloud condensation nuclei and the associated change in the cloud albedo. Other measurable manifestations of the indirect effect include the change in the cloud droplet size and number concentration and changing liquid water path [29–31]. Since the droplet generation efficiency of aerosols depends on their size and hygroscopicity, the measurement of the aerosol number concentration must be accompanied by the determination of the aerosol effective radius and chemical composition.

The left column of Table 2 lists the cloud and aerosol characteristics that are required for a reliable monitoring of the indirect aerosol effect on climate and its anthropogenic component, whereas the right column lists the minimum set of retrievable parameters that can be used to determine the required cloud and aerosol characteristics. The respective APS minimum measurement requirements listed in Appendix A include the retrieval of the column cloud optical thickness and the average column cloud droplet size distribution as well as the column aerosol optical thickness and the average column values of the effective radius and effective variance of the aerosol size distribution and the real part of the aerosol refractive index for each mode of a bimodal aerosol population.

Note that the cloud and aerosol particle number concentrations listed in the left column of Table 2 are derived rather than directly retrieved quantities, i.e., deduced from the column optical thickness and

the particle extinction cross section (a function of size distribution, refractive index, and particle shape). The accuracy with which the number concentrations must be determined is very difficult to achieve and necessitates the retrieval of the cloud droplet and aerosol size distributions and the aerosol refractive index with precision unattainable with instruments based on radiometric measurements alone [32,33]. Assuming rather than retrieving the effective variance of the cloud droplet and aerosol size distributions and the aerosol refractive index can lead to even larger errors in the retrieved number concentrations.

4. Measurement accuracy requirements

The criteria for specifying the corresponding measurement accuracy requirements in Appendix A must be based on the desire to detect plausible changes of the aerosol radiative forcing estimated to be possible during the next 20 years and to determine quantitatively the contribution of this forcing to the planetary energy balance. A significant global mean flux change can be defined as 0.25 W/m^2 or greater based on the consideration that anticipated increases of greenhouse gases during the next 20 years will cause a forcing of about 1 W/m^2 [2].

The estimated plausible 20-year change of the global mean aerosol optical thickness is 0.04, whereas the global mean optical thickness change required to yield the 0.25 W/m^2 flux change is 0.01 [2]. These numbers justify the proposed threshold accuracy and precision for the aerosol optical thickness measurement.

The accuracy and precision indicated for the aerosol size distribution measurement are dictated by the requirement to measure the aerosol number concentration with an accuracy good enough for detecting the effect of increasing CCN concentration on cloud properties. The latter should be at least 30% or better [34]. The strong dependence of the extinction cross section on the effective radius and effective variance makes the retrieval of aerosol number concentration very difficult and necessitates high-accuracy measurements of the size distribution [32,33]. Accurate retrievals of the aerosol particle size are also needed in order to determine the cloud condensation efficiency of aerosols [29,35].

The measurement accuracy and precision indicated for the real part of the aerosol refractive index are determined by the need to identify the aerosol chemical composition. The latter is required in order to identify hygroscopic aerosols, discriminate between natural and anthropogenic aerosol species, and estimate the imaginary part of the refractive index to provide an independent check on the retrieved single-scattering albedo.

The measurement accuracy and precision for the cloud particle size distribution are dictated by the need to detect a flux change of 0.25 W/m^2 or greater [2], reliably detect a change of cloud particle size caused by increasing CCN concentrations [29–31], and determine the cloud droplet number concentration with an accuracy of at least 30%.

5. Implementation issues

Passive remote-sensing instruments measure the reflected solar radiation or the thermal radiation emitted by the atmosphere–surface system. The instruments based on measurements of the reflected sunlight can be classified by whether they measure only the radiance (i.e., the first Stokes parameter, I) or the radiance plus one or more of the remaining Stokes parameters describing the polarization state of the

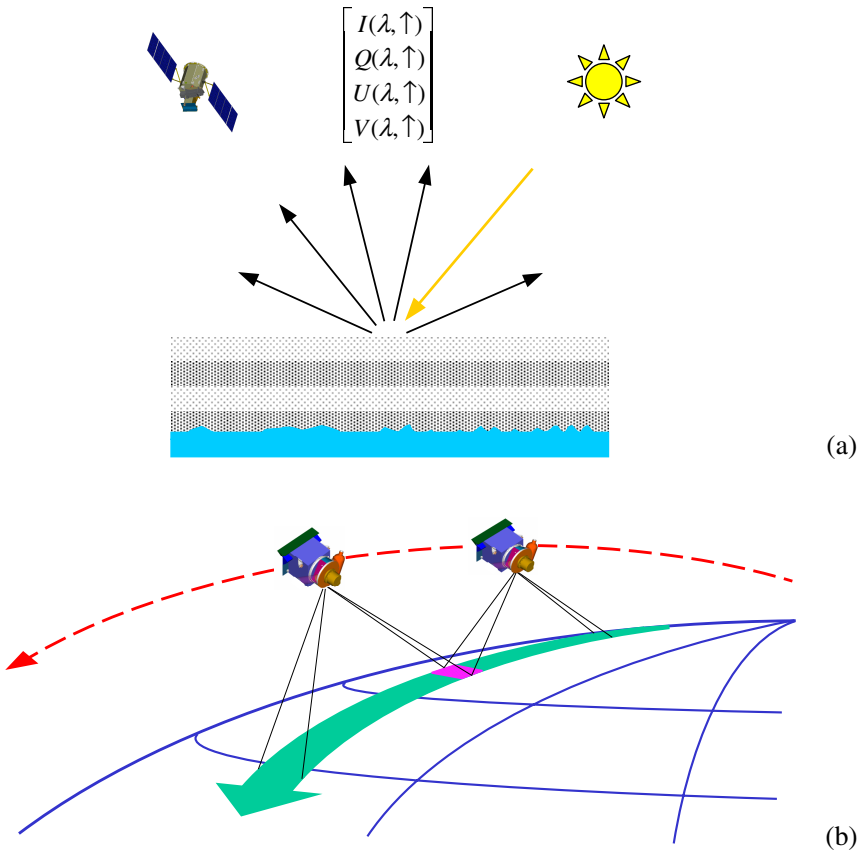

Fig. 1. (a) Classification of satellite instruments measuring various characteristics of the reflected sunlight. The Stokes parameters I, Q, U, and V of the reflected light vary with wavelength, λ, and scattering direction, $\uparrow$. (b) Along-track scanning photopolarimeter. By scanning along the ground track, the instrument observes the same piece of real estate from different viewing directions, thereby providing multi-angle measurements of the reflected radiance and polarization.

reflected radiation (i.e., Q, U, and V); by the measurement accuracy; by the number of spectral channels and the total spectral range covered; and by the number and range of viewing directions from which a scene location is observed (Fig. 1(a)). At the bottom of the corresponding hierarchy of aerosol retrieval algorithms is the National Oceanic and Atmospheric Administration (NOAA) operational algorithm based on channel-1 Advanced Very High Resolution Radiometer (AVHRR) radiance data [12]. At the top of this hierarchy would be an instrument providing high-precision measurements of all four Stokes parameters in multiple spectral channels covering a spectral range from near-UV to short-wave IR wavelengths and at multiple viewing directions covering a significant angular range.

Theoretical sensitivity analyses [32] and analyses of actual high-precision radiance and polarization data [36,37] show that retrieval algorithms based on radiance measurements alone cannot provide retrieval capability for some parameters or the accuracies summarized in Section 4 and Appendix A. The only instrument capable of retrieving aerosol and cloud properties with accuracy high enough for long-term monitoring of the aerosol radiative forcing is a high-precision multi-angle photopolarimeter performing

measurements at wavelengths from ~ 0.4 to ~ 2.4 μm [32,36,37]. This instrument takes advantage of the strong sensitivity of the polarization state of sunlight reflected by the atmosphere to aerosol and cloud particle microphysics [24,38].

At present, polarimeters designed for such high-precision measurements (such as the Earth Observing Scanning Polarimeter [39] and the Research Scanning Polarimeter [36]) obtain the multi-angle coverage by scanning along the platform ground track (Fig. 1(b)). The weakness of an along-track-scanning instrument is that it does not provide spatial coverage comparable to that of an imager. Therefore, the along-track-scanning multi-spectral photopolarimeter should be flown in combination with a multi-spectral imager such as the Visible/Infrared Imager/Radiometer Suite (VIIRS; http://www.ipo.noaa.gov/Technology/viirs_summary.html). The photopolarimeter provides detailed aerosol information within a narrow swath along the ground track, which can be used to calibrate the imager retrieval algorithm and thereby obtain improved aerosol retrievals within the much wider swath of the imager. It can be argued that if the spectral radiances in all VIIRS channels within any continuous region of the VIIRS image are consistent with those predicted by the retrieved aerosol properties from the photopolarimeter, then the VIIRS-retrieved aerosol optical thickness and fraction of the fine mode aerosol are valid. While it is unlikely that such regions can extend to the edge of the VIIRS scan, i.e., 1500 km from the photopolarimeter ground track, it is expected that they often would extend to distances from the ground track significantly greater than 50 or even 100 km.

The quantification of aerosol forcing and reducing its uncertainty may be an incomplete endeavor without an integrated approach that includes, in addition to space-based measurements, correlative measurements (from ground networks [40], aircraft [41–43], balloons, ships [44,45]) and modeling [7]. The correlative measurements can be used for validating satellite retrievals and can provide crucial information on the relationship between the aerosol chemical composition and the imaginary part of the refractive index (single-scattering albedo) [35,46]. Unlike space-borne measurements, the correlative measurements can provide direct information about physics and chemistry of aerosols and aerosol-cloud interactions [30,31,35]. The accuracy of aerosol and cloud modeling is the ultimate measure of our understanding of the processes that govern the formation, processing, and transport of aerosols and their interaction with clouds [5,47–49]. Furthermore, modeling can potentially be used to fill the gaps in the spatial and/or temporal coverage of satellite measurements.

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Appendix A. Specific APS aerosol and cloud science requirements

A.1. Aerosol optical thickness

Aerosol optical thickness is defined as the atmospheric column extinction (scattering+absorption) optical thickness of modes 1 and 2 of the bimodal aerosol populations at multiple wavelengths within the

Table 3
Aerosol optical thickness requirements

Parameter	Threshold science requirement
Horizontal cell size (nadir)	6 km
Vertical cell size	Total atmospheric column
Measurement range #	0–5
Measurement accuracy #	0.02 or 7% over ocean 0.04 or 10% over land
Measurement precision #	0.01 or 5% over ocean 0.03 or 7% over land

Table 4
Aerosol particle size distribution requirements

Parameter	Threshold science requirement
Horizontal cell size (nadir)	6 km
Vertical cell size	Total atmospheric column
Measurement range	0.1–5 μm for r_{eff} 0–3 for v_{eff}
Measurement accuracy	Greater of 0.1 μm or 10% for r_{eff} Greater of 0.3 or 50% for v_{eff}
Measurement precision	Greater of 0.05 μm or 10% for r_{eff} Greater of 0.1 or 40% for v_{eff}

0.35–2.5 μm spectral range (#—applies to total column optical thickness of each mode). The measurement requirements in Table 3 apply only under clear-sky conditions and only to sub-satellite pixels. Clear-sky conditions are defined as the absence of liquid clouds and optically thick cirrus clouds within the pixel.

A.2. Aerosol particle size distribution

Measurement of the size distribution of the bimodal aerosol population in terms of the effective radius v_{eff} and effective variance v_{eff} of each mode. The effective radius is the ratio of the third moment of the aerosol size distribution to the second moment (Eqs. (1) and (3)). The effective variance characterizes the width of the size distribution (Eq. (2)). The measurement requirements in Table 4 apply only under clear conditions and only to sub-satellite pixels. Clear-sky conditions are defined as the absence of liquid clouds and optically thick cirrus clouds within the pixel.

A.3. Aerosol refractive index, single-scattering albedo, and shape

Measurement of the real part of the refractive index m and the single-scattering albedo ϖ of each mode of the bimodal aerosol population at multiple wavelengths within the 0.35–2.5 μm spectral range and determination whether aerosol particles are spherical or nonspherical. Non-sphericity is detected when

Table 5
Aerosol refractive index and single-scattering albedo requirements

Parameter	Threshold science requirement
Horizontal cell size (nadir)	6 km
Vertical cell size	Total atmospheric column
Measurement range	1.3–1.7 for m
	0–1 for ϖ
Measurement accuracy	0.02 for m
	0.03 for ϖ
Measurement precision	0.01 for m
	0.02 for ϖ

Table 6
Liquid cloud optical thickness requirements

Parameter	Threshold science requirement
Horizontal cell size (nadir)	6 km
Vertical cell size	Total atmospheric column
Measurement range	0–300
Measurement accuracy	Greater of 0.1 or 8%
Measurement precision	Greater of 0.1 or 8%

the value $S = (L_{\max}/L_{\min} - 1) > 0.3$, where $L_{\max}$ is the maximum length of the particle and $L_{\min}$ is the minimum length of the particle. The measurement requirements in Table 5 apply only under clear conditions and only to sub-satellite pixels. Clear-sky conditions are defined as the absence of liquid clouds and optically thick cirrus clouds within the pixel.

A.4. Liquid cloud optical thickness

Liquid cloud optical thickness is defined as the column extinction (scattering+absorption) vertical optical thickness at multiple wavelengths within the 0.35–2.5 μm spectral range. The measurement requirements in Table 6 apply only to sub-satellite pixels.

A.5. Liquid cloud particle size distribution

The effective radius v_{eff} and effective variance v_{eff} of a monomodal cloud droplet size distribution. The effective radius is the ratio of the third moment of the size distribution to the second moment. The effective variance characterizes the width of the size distribution. The measurement requirements below apply only to sub-satellite pixels (Table 7).

Table 7
Liquid cloud particle size distribution requirements

Parameter	Threshold science requirement
Horizontal cell size (nadir)	6 km
Vertical cell size	Total atmospheric column
Measurement range	0.1–50 μm for r_{eff} 0–2 for v_{eff}
Measurement accuracy	Greater of 1 μm or 10% for r_{eff} Greater of 0.05 or 50% for v_{eff}
Measurement precision	Greater of 0.5 μm or 5% for r_{eff} Greater of 0.04 or 40% for v_{eff}

Table 8
Single-scattering albedo goals

Parameter	Science goal requirement
Horizontal cell size (nadir)	6 km
Vertical cell size	Total atmospheric column
Measurement range	0.3–1.0
Measurement accuracy	0.02
Measurement precision	0.01

Appendix B. APS aerosol and cloud science goals

B.1. Single-scattering albedo derived from ocean glint observations

The single-scattering albedo is derived from the aerosol attenuation of the glint reflectance in the 550 and 670 nm channels relative to that at 2250 and 1610 nm for optical thicknesses in the range 0.2–0.4 at 550 nm [50] (Table 8).

B.2. Single-scattering albedo derived from the spectral contrast technique

The algorithm takes advantage of how the spectral contrast between 412 and 488 nm is changed by aerosols in a Rayleigh scattering atmosphere to retrieve the single-scattering albedo. It exploits the fact that surfaces are dark at 412 nm, including over deserts, in order to minimize the error due to surface effects. An aerosol index derived from the spectral contrast is a byproduct that can be used to distinguish heavy dust from clouds.The algorithm works well over all surfaces including land and ocean. However, for very bright surfaces such as desert, a minimum optical thickness of 0.7 is needed for the accuracy of the retrieval. Multi-angle radiances and polarization from APS will be used to constrain which aerosol model to use for each retrieval. The use of angular and polarization information is expected to further relax the minimum required optical thickness to lower aerosol loading and to improve the accuracy of single-scattering albedo obtained from radiance measurements alone (Table 9).

Table 9
Single-scattering albedo goals

Parameter	Science goal requirement
Horizontal cell size (nadir)	6 km
Vertical cell size	Total atmospheric column
Measurement range	0–1.0
Measurement accuracy	0.03
Measurement precision	0.02

Table 10
Aerosol optical thickness goals

Parameter	Science goal requirement
Horizontal cell size	6 km
Vertical cell size	Total atmospheric column
Measurement range	0–5
Measurement accuracy	0.02 or 7% over ocean 0.05 or 10% over land
Measurement precision	0.02 or 7% over ocean 0.05 or 10% over land

Table 11
Fine mode aerosol goals

Parameter	Science goal requirement
Horizontal cell size	6 km
Vertical cell size	Total atmospheric column
Measurement range	0–1
Measurement accuracy	0.1 over ocean
Measurements precision	0.05 over ocean

B.3. Aerosol optical thickness derived from APS—VIIRS combined inversion

The aerosol optical thickness is derived from the VIIRS radiance data over distances of 50–100 km or greater from the APS ground track assuming the APS-retrieved aerosol spectral refractive indices, single-scattering albedo, and the size, width, and nonsphericity of the modes. The retrieval is considered valid when the spectral variation of the retrieved optical thickness using VIIRS data matches that of the APS optical thickness to better than 7% (Table 10).

B.4. Fraction of fine mode aerosol derived from APS—VIIRS combined inversion

The fine mode fraction of the total aerosol column optical thickness is derived from the VIIRS data over distances of 50–100 km from the APS ground track assuming the APS-retrieved aerosol spectral refractive indices, single-scattering albedo, and the size, width, and nonsphericity of the modes. The

retrieval is considered valid when the spectral variation of the retrieved optical thickness using VIIRS data matches that of the APS optical thickness to better than 7% (Table 11).

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