Retrieval analysis of aerosol-size distribution with simulated extinction measurements at SAGE III wavelengths

Pi-Huan Wang, Geoffrey S. Kent, M. Patrick McCormick, Larry W. Thomason, and Glenn K. Yue

The retrieval of aerosol-size distribution from simulated aerosol-extinction-coefficient measurements of the new satellite instrument, the Stratospheric Aerosol and Gas Experiment (SAGE) III, is investigated. A detailed discussion on the aerosol-size-distribution information content of the SAGE III aerosol-extinction-coefficient measurement is provided. Results of the investigation indicate that unimodal as well as bimodal log-normal size distributions can be inferred. In addition, it is shown that a shape-constraint-free size distribution can be derived from SAGE III aerosol measurements by use of the randomized minimization search technique and the optimal estimation theory.

Key words: Remote sensing, aerosol-extinction coefficient, aerosol-size distribution retrieval.
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1. Introduction

Understanding the importance of the effect of aerosols on the Earth's atmosphere has become a major focus of research in recent years. Aerosols can interact directly with solar and terrestrial radiation by absorption and scattering, or indirectly through cloud radiative properties. Thus aerosols modify the radiation budget of the atmosphere–Earth system and affect the climate.[1] Stratospheric aerosols also have a profound effect on ozone concentration through their interaction with solar radiation and involvement in heterogeneous chemistry, particularly following major volcanic eruptions and during winter in the Antarctic region.[2–4] A description of the aerosols requires information on their size distribution, composition (refractive index), and shape. The objective of this study is to investigate the retrieval of the size distribution from aerosol-extinction-coefficient measurements of the Stratospheric Aerosol and Gas Experiment (SAGE) III.

Since 1978 the National Aeronautics and Space Administration (NASA) has launched three satellite sensors to measure the global distribution of stratospheric as well as tropospheric aerosols by the use of the solar occultation technique. They are the Stratospheric Aerosol Measurement (SAM) II, SAGE I, and SAGE II. SAM II is a single-channel satellite instrument that measured the aerosol-extinction profile at the 1-μm wavelength aboard the Nimbus-7 satellite. It provided measurements from October 1978 to January 1994 in the polar regions. The SAGE I instrument is a four-channel device aboard the Applications Explorer Mission II satellite. It measured the concentrations of O_3 and NO_2 and aerosol extinction at 0.45 and 1.0 μm between approximately 80 °S and 80 °N from February 1979 to November 1982. The SAGE II instrument is an advanced version of SAGE I. It is equipped with seven channels for measuring the concentrations of O_3, NO_2, and H_2O and aerosol extinction at 0.385-, 0.453-, 0.525-, and 1.02-μm wavelengths (Table 1), also between 80 °S and 80 °N. The SAGE II instrument, which is aboard the Earth Radiation Budget Satellite, has provided measurements since October 1984 and remains operational today. It should be mentioned that by use of the solar occultation technique, the above three satellite sensors provide intensity self-

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Table 1. SAGE II and SAGE III

Sensor	Wavelength (μm)	Species
SAGE II	0.385	Aerosol
	0.448	NO_2
	0.453	Aerosol
	0.525	Aerosol
	0.600	O_3
	0.940	H_2O
	1.02	Aerosol
SAGE III	0.290	O_3
	0.385	Aerosol
	0.448	NO_2
	0.453	Aerosol
	0.525	Aerosol
	0.600	O_3
	0.660	NO_3
	0.760	O_2, Aerosol
	0.940	H_2O, Aerosol
	1.02	Aerosol
	1.55	Aerosol

calibrated measurements that are important for long-term-change determination.

The SAGE III, the latest of the occultational remote sensors,[5] is proposed for the early Earth Observing System platforms. Its 11 channels cover a wavelength range from 0.28 to 1.550 μm, wider than all its predecessors (Table 1). Most significantly, it uses the latest technique of the charge coupled device (CCD) linear array of detectors in the wavelength range between 0.280 and 1.03 μm. By use of the CCD linear-array technique, measurements of multiple absorption features of particular gaseous species, such as O_3, NO_2, H_2O, NO_3, and OClO, and the multiple-wavelength broadband extinction by aerosols can be achieved, thus greatly increasing the accuracy of the retrieval processes. Most important, because it is able to measure absorption features of a particular gaseous species, this new instrument is capable of calibrating its measurements in both wavelength and intensity, enhancing long-term-trend observations. Because the instrument is designed for measuring the absorption of the O_2–*A* band near 0.760 μm, the molecular density and the temperature profile can be determined from SAGE III observations, making the retrieval processes self-sufficient. In addition the instrument is designed to provide measurements in both the solar and the lunar occultation modes, considerably increasing the spatial resolution and allowing for the measurement of nighttime chemical species such as NO_3 and OClO.

2. SAGE III Aerosol-Extinction Measurements

Multiwavelength aerosol-extinction-coefficient measurements contain information on aerosol-size distribution.[6,7] Following the Mie theory, the particulate-extinction coefficient (ϵ) at a given wavelength can be expressed as

$$\epsilon = \int Q_e \pi r^2 \frac{\mathrm{d}n}{\mathrm{d}r}\,\mathrm{d}r, \tag{1}$$

where r is the particle radius, Q_e is the Mie extinction efficiency factor, and $\mathrm{d}n/\mathrm{d}r$ is the differential particle-size distribution. By defining a kernel function

$$\kappa_e = \frac{3}{4r} Q_e,$$

we have

$$\epsilon = \int \kappa_e \frac{\mathrm{d}v}{\mathrm{d}r}\,\mathrm{d}r, \tag{2}$$

where $\mathrm{d}v/\mathrm{d}r$ ($= 4/3\pi r^3 \mathrm{d}n/\mathrm{d}r$) is the differential particle-volume-size distribution. Thus the particulate extinction is a convolution of two functions: the kernel function κ_e and the particle-volume-size distribution. The kernel function provides a measure of the relative contribution of particles of different volume sizes to the measured or the calculated extinction. Hence it reflects the sensitivity of ϵ to particles of various sizes. The kernel functions at the seven wavelengths of the SAGE III aerosol measurements, normalized to their corresponding peaks, are presented in Fig. 1. In the analysis of the kernel function, we have used the refractive indices suitable for stratospheric aerosols at the SAGE III wavelengths (Table 2). As pointed out by King,[8] the refractive-index sensitivity of the retrieval based on spectral-attenuation measurements is quite weak, affecting the inverted size distribution slightly by shifting its magnitude and radii while maintaining its overall shape.

If a value of 0.5 of the normalized kernel function is used as a measure of the richness of the particle-size information content, the results in Fig. 1 indicate that most of the information is contained in the radius range from approximately 0.1 to 1.5 μm. Therefore, by incorporation of a channel at 1.55 μm, the set of the SAGE III aerosol-extinction measurements extends the information content from the 1.0-μm particle radius of the SAGE II instrument[7] to approximately 1.5 μm. Note that the distribution of the peak of the normalized kernel functions shows a particle-radius range between approximately 0.2 and 1.0 μm. Thus this radius range constitutes the primary resolvable particle-size distribution in the multiwavelength aerosol-extinction measurement made by the SAGE III instrument. As is shown in Section 3, the SAGE III spectral-extinction measurements allow for derivation of the aerosol-size distribution in a variety of conditions, including the background stratosphere and volcanic situations such as those after the April 1982 El Chichón and June 1991 Pinatubo eruptions. The corresponding information in the case of SAGE II is in the radius range

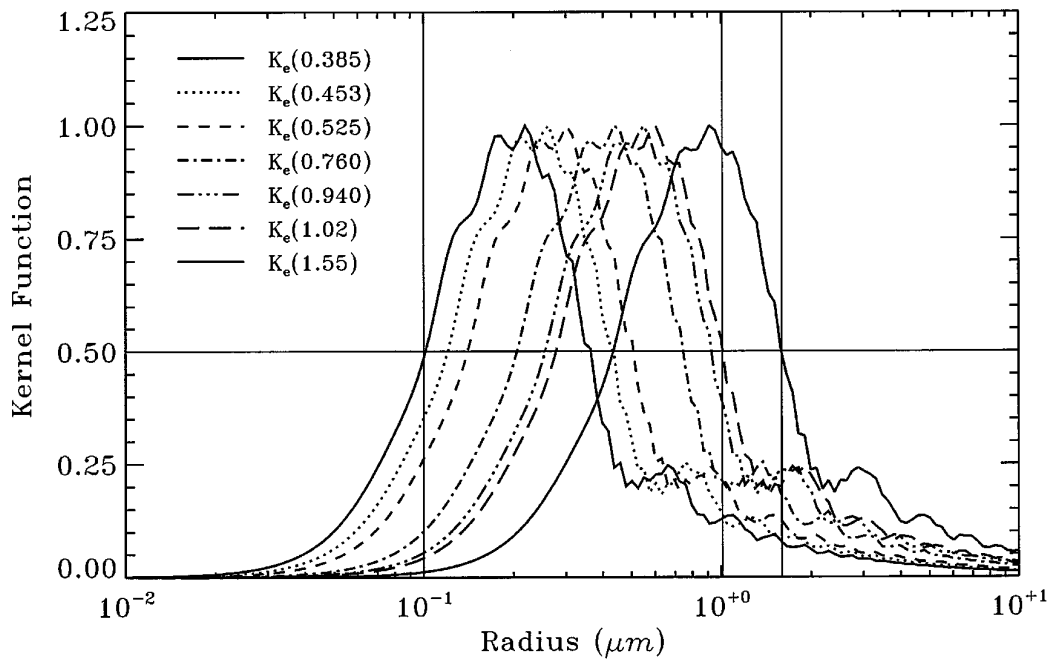


Fig. 1. Normalized kernel function at SAGE III wavelengths.

from approximately 0.2 to 0.8 μm.[7] Also, with the aerosol-extinction measurements at the 0.760-μm and 0.940-μm wavelengths, located in the spectral gap between 0.525 and 1.02 μm of the SAGE II observations, the SAGE III measurements would provide stronger constraints in particle-size-distribution retrieval.

3. Aerosol-Size-Distribution Retrieval

Several methods have been used in the past to retrieve aerosol-size distributions based on SAGE II aerosol-extinction-coefficient measurements. In general these methods can be grouped into two categories: the shape-constrained method and the shape-constraint-free method. In the case of the shape-constrained method, the aerosol-size distribution is modeled by an analytic function, such as a log-normal expression, and the segment power-law formula.[7,9,10] Parameters of those functions are determined in concert with the aerosol-extinction measurements at SAGE II wavelengths. Because the SAGE II instrument measures aerosol extinction at four different wavelengths, only a unimodal log-normal expression can be determined. In the case of the shape-constraint-free method, the randomized minimization search technique (RMST) developed by Heintzenberg *et al.*[6] is applied.[11,12] In the present study these two approaches are investigated based on simulated SAGE III aerosol-extinction measurements, and the retrieved size distributions are compared. In addition, the application of Rodgers' optimal estimation (OE) theory[13,14] to the SAGE III aerosol-size-distribution retrieval is presented. Note that, for reasons of convenience and effectiveness, the *in situ* aerosol data measured at discrete size bins are often translated into analytic expression (e.g., Oberbeck *et al.*[15]). The analytic expression is also in concordance with the smoothness of the aerosol-size distribution from the microphysical point of view.

Table 2. Refractive Index at SAGE III Aerosol Wavelengths

Wavelength (μm)	Refractive Index[a]
0.385	$1.478 + i0.000$
0.453	$1.471 + i0.000$
0.525	$1.465 + i0.000$
0.760	$1.454 + i0.000$
0.940	$1.451 + i0.000$
1.02	$1.448 + i0.000$
1.55	$1.427 + i0.000$

[a]Sulfuric acid–water droplets (75% H_2SO_4, 25% H_2O by weight) at $P = 50$ mbars, $T = 218$ K.[7]

A. Retrieval Methods

By use of a nonlinear least-squares (NLS) algorithm, the parameters of analytic expressions can be retrieved from observed multiwavelength aerosol-extinction coefficients. A description of such a retrieval method for the SAGE II aerosol-extinction observations can be found in the paper by Wang *et al.*[7] In the present study we extend their application to the extinction measurements at SAGE III wavelengths. Because the instrument measures aerosol-extinction coefficients at seven wavelengths, unimodal as well as bimodal log-normal size distributions can be determined from SAGE III observations. Generally, under nonvolcanic or background conditions, a unimodal expression is useful in describing aerosol population,[16,17] whereas under volcanic conditions a bimodal expression is needed to capture the essential features.[15,18–20]

To study the size-distribution retrieval, a set of SAGE III aerosol-spectral-extinction measurements is generated based on the Mie theory for a given size distribution. This size distribution can be a unimodal or a bimodal log-normal expression or a nonanalytic set based on existing *in situ* observations. The NLS algorithm is then applied to the set of aerosol extinctions to retrieve the parameter of the analytic expression desired. The iteration of the retrieval calculation is terminated when the difference between the predicated extinctions at SAGE III wavelengths from the derived size distribution and the simulated extinction measurements reaches the expected uncertainty of the SAGE III observation, or the number of the iteration equals a preset value. For convenience, we have used both the unimodal and the bimodal log-normal expressions in the aerosol-extinction simulation. The analytic expression of a unimodal log-normal size distribution can be presented as

$$\frac{\mathrm{d}n}{\mathrm{d}r} = \frac{N_0}{\sqrt{2\pi}r \ln \sigma} \exp\left[-\frac{\ln^2(r/r_m)}{2 \ln^2 \sigma}\right], \tag{3}$$

where N_0 is the aerosol number concentration [in inverse cubic centimeters (cm^{-3})], r_m (in micrometers) is the mode radius, and σ is the associated standard deviation of the log-normal expression. It has been shown that the size distribution of the background stratospheric aerosols can be represented by a unimodal log-normal size distribution with the values 10 cm^{-3}, 0.0725 μm, and 1.86 for N_0, r_m, and σ, respectively. In the present investigation a 10% error is used in the retrieval analysis, and the maximum number of the iterations is set at 20.

In the RMST analysis, it is convenient to use the derived analytic expression described above as an initial guess. Twelve bins of aerosol radius centered between 0.12 and 1.22 μm are used because SAGE III extinctions contain useful size information approximately in this radius range (see Section 2). Readers are referred to the work of Heintzenberg *et al.*[6] for a detailed description of the RMST algorithm. Similarly the iteration of the RMST calculation is terminated when the difference between the predicated extinctions and the simulated extinction measurements reaches the uncertainty of the SAGE III observations, or the number of the iteration equals a preassigned value.

To provide an uncertainty estimate of the NLS- and the RMST-derived size distributions, the associated standard deviation of the retrieval is examined. This examination is accomplished by the assumption that the derived size distribution is the true aerosol-size distribution. This true size distribution is then used to simulate aerosol-extinction measurements of the SAGE III instrument by incorporation of an error up to 10% generated by use of a random number generator (uniform distribution). The set of simulated extinctions is then used to infer the aerosol-size distribution. Fifty such simulation and retrieval computations are carried out to determine the standard deviation of the derived size distribution. A similar approach to estimation of the uncertainty of the retrieved size distribution is used in the SAGE II aerosol analysis.[7]

The OE method of retrieval has been described by Rodgers[13,14] in detail. With reference to an *a priori* estimate, the retrieval determines a solution that is in concert with the physics of the measurement and with the statistical constraints of the covariance of the *a priori* estimate and the covariance of the measurement. Because of the lack of sufficient statistics of the aerosol-size distribution, the log-normal size distribution of the background stratospheric aerosols is used as the *a priori* estimate in the OE inversion. The covariance of the *a priori* estimate and the spectral-extinction measurement are assumed to be diagonal, with the diagonal elements equal to $(0.95)^2$ and $(0.01)^2$, respectively. Note that, with the *a priori* uncertainty being so large, the retrieved solution has very little dependence on the *a priori* distribution used in the inversion. It should be mentioned that aerosol-size distribution has been determined by use of the constrained linear inversion[21] based on spectral measurements (e.g., Spinhirne and King[22]). As indicated by King,[8] when the imposed Twomey[21] smoothing constraint is replaced by the inverse of an *a priori* estimate of the solution covariance matrix, the algorithm of the constrained linear inversion is equivalent to the OE analysis. In the present application of the OE retrieval, the seven-channel extinction-coefficient measurements from the SAGE III instrument are used to determine the aerosol population in seven radius-size bins centered between 0.175 and 1.075 μm with a bin width of 0.15 μm. Figure 2 illustrates the averaging kernel of the OE retrieval of the SAGE III spectral-extinction measurements. According to Rodgers,[13,14] the retrieval at any size bin is an average of the entire true size distribution weighted by the curve of the averaging kernel.

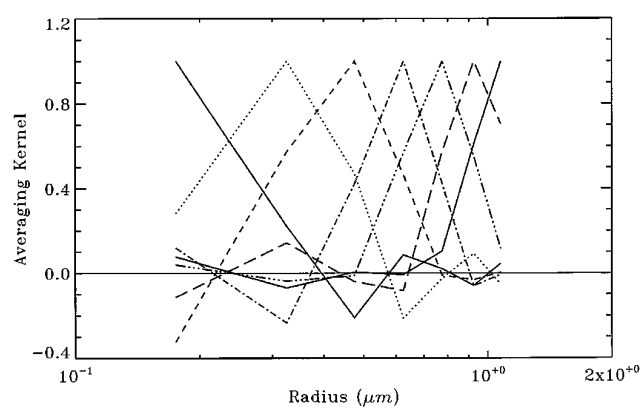


Fig. 2. Normalized averaging kernels corresponding to the seven size bins used in the OE retrieval of the SAGE III aerosol spectral-extinction measurements (see text, also Rodgers[13,14]).

B. Discussion of Results

As a first example of the retrieval analysis, a bimodal log-normal expression (Table 3) is used in the NLS size-distribution inversion based on simulated SAGE III extinction measurements with a unimodal log-normal size distribution appropriate for the background stratospheric aerosols. The choice of the initial guess is somewhat arbitrary. As shown in Fig. 3, the initial guess is notably different from the size distribution used in the simulation computation. The results of the analysis along with the RMST and the OE retrievals are presented in Fig. 3. With reference to the size distribution used in the simulation, the solutions from those three different inversions are quite good. Note, in this example, that the true size distribution in the extinction simulation is exactly the *a priori* estimate used in OE analysis. An OE retrieval by use of an *a priori* distribution, which is the same bimodal expression used in the NLS computation, shows a slightly less satisfactory result (not shown). To demonstrate the capability of retrieving bimodal log-normal aerosol-size distribution from SAGE III extinction measurements, a study of the NLS retrieval is conducted with simulated extinctions at SAGE III wavelengths with aerosol-size distributions observed after the April 1982 El Chichón and the June 1991 Pinatubo eruptions[17,20] (Table 3). The results of this NLS analysis are given in Fig. 4. Note that the same initial guess used in the previous example is used in this analysis. A satisfactory solution of the NLS retrieval is apparent. Also shown in Fig. 4 are the RMST and the OE retrievals. As can be seen, the RMST solution is equally satisfactory. In the case of OE analysis, the solution is also quite good, except for the bins around 0.3 and 1.1 μm.

To examine the effect of the initial guess on the NLS and the RMST retrievals, an analysis is made with simulated aerosol extinctions based on the observed volcanic aerosol-size distributions from El Chichón and Pinatubo that were mentioned above and with the unimodal distribution of the background stratospheric aerosols as the initial guess.

Table 3. Parameter Values of the Analytic Expression

Log Normal	Parameter	Truth[a] Background[16]	Truth[a] El Chichón[15]	Truth[a] Pinatubo[20]	Initial Guess
Unimodal	N_0 (cm^{-3})	10			10
	r_m (μm)	0.0725			0.0725
	σ	1.86			1.86
Bimodal	$N_{0,1}$ (cm^{-3})		5.1	2.1	1.0
	$r_{m,1}$ (μm)		0.19	0.33	0.076
	σ_1		1.65	1.5	1.86
	$N_{0,2}$ (cm^{-3})		2.8	3.1	1.0
	$r_{m,2}$ (μm)		0.59	0.60	0.50
	σ_2		1.2	1.3	1.55

[a]Aerosol-size-distribution parameters used in the SAGE III extinction-measurement simulation.

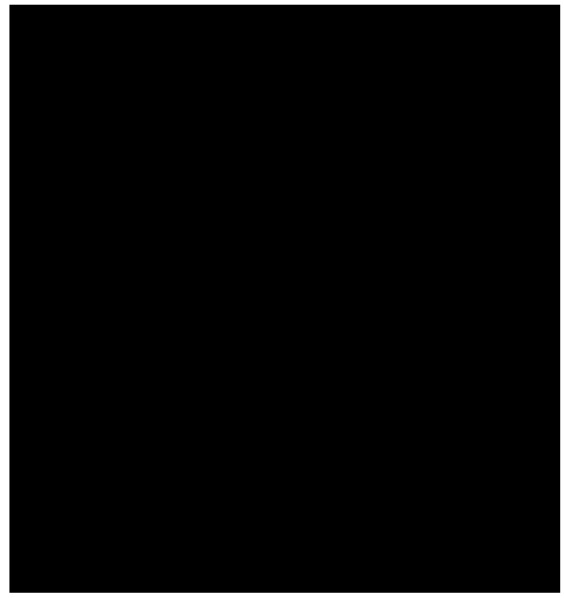
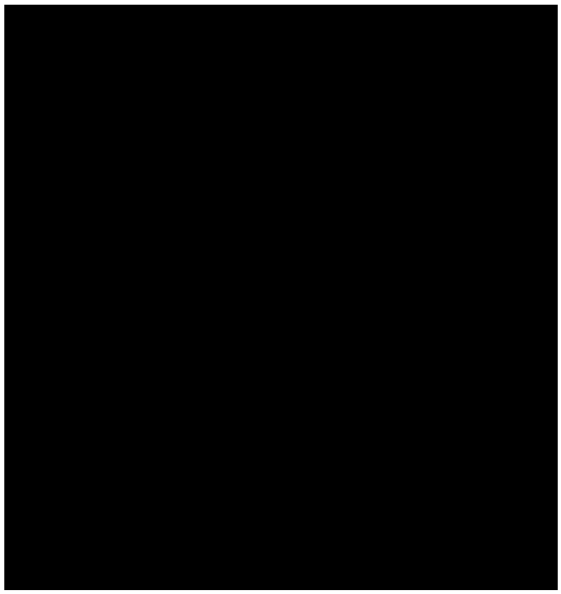


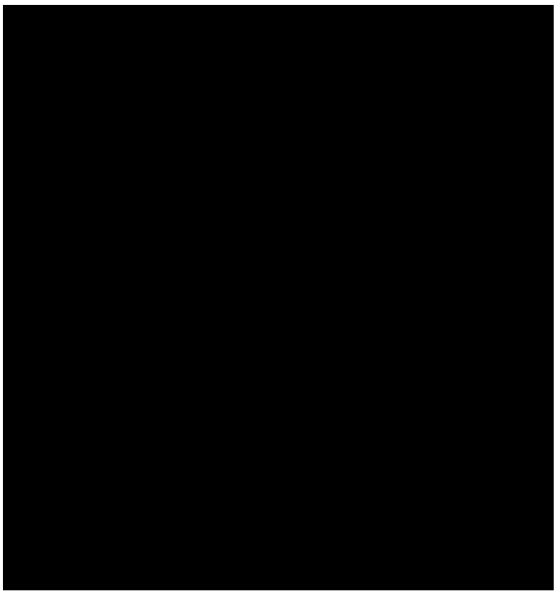
Fig. 3. Aerosol-size distribution retrieval analysis by use of simulated SAGE III aerosol-extinction measurements according to the unimodal log-normal size distribution of the background stratospheric aerosols. A bimodal log-normal expression is used as the initial guess in the NLS retrievals. The solution of the bimodal expression is then used in the RMST analysis. In the OE retrieval, the *a priori* profile is the unimodal log-normal distribution of the stratospheric background aerosols.

The results are presented in Fig. 5. (The solutions from OE retrieval in Fig. 4 are also shown in Fig. 5.) As expected, the NLS and the RMST solutions are less satisfactory in comparison with the results shown in Fig. 4. Nevertheless the NLS retrieval in Fig. 5 is able to portray most of the large mode of the true size distribution (in the radius range between approximately 0.3 and 0.9 μm), although it misses a large portion of the small mode, especially for radii less than approximately 0.2 to 0.3 μm. This feature is particularly evident for the El Chichón analysis and is, in fact, consistent with the characteristics of the size-distribution information content described in Subsection 3.A., which shows that the primary size-distribution information is within the size range between approximately 0.2 and 1.0 μm. Note that between the peaks of the two modes of the observed Pinatubo aerosol-size distribution, the RMST analysis appears to be able to capture the small mode-size distribution to some extent and show closer results to the true size distribution.

At this point it is noteworthy that a similar feature of the NLS retrieved unimodal size distribution can be found in Wang *et al.*[7] Based on SAGE II aerosol-extinction measurements at four wavelengths obtained near Laramie, Wyoming, on 30 November 1984, Wang *et al.* have retrieved unimodal log-normal size distributions that show larger mode radii and smaller standard deviations of the log-normal expression than the corresponding parameters of the background stratospheric aerosols.[7,16]

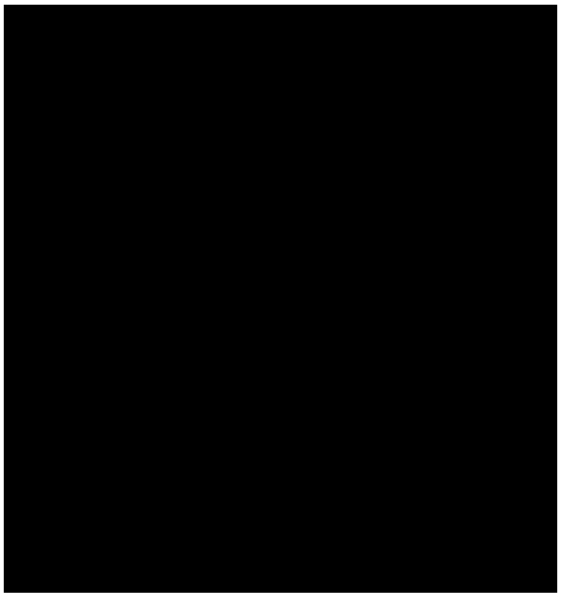


(a)



(b)

Fig. 4. Aerosol-size-distribution retrieval analysis by use of simulated SAGE III aerosol-extinction measurements according to the observed aerosol size distributions after (a) the April 1982 El Chichón and (b) the June 1991 Pinatubo volcanic eruptions. A bimodal log-normal expression is used as the initial guess in the NLS retrievals. The solution of the bimodal expression is then used in the RMST analysis. In the OE retrieval, the *a priori* profile is the unimodal log-normal distribution of the stratospheric background aerosols.



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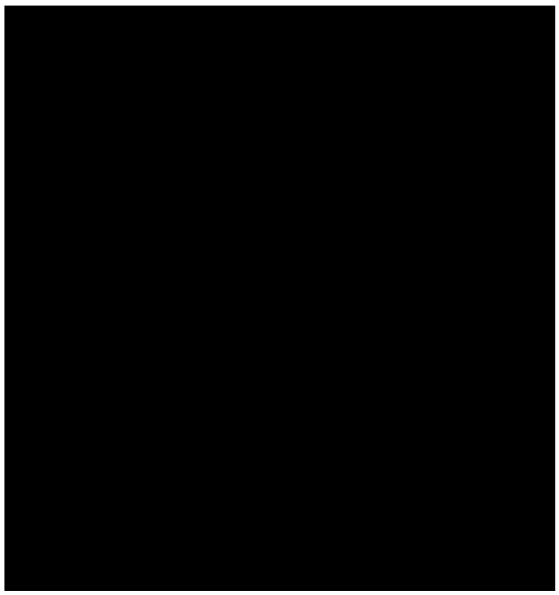

(b)

Fig. 5. Aerosol-size-distribution retrieval analysis by use of simulated SAGE III aerosol-extinction measurements according to the observed aerosol-size distributions after (a) the April 1982 El Chichón and (b) the June 1991 Pinatubo volcanic eruptions. A unimodal log-normal expression of the background stratospheric aerosols is used as the initial guess in the NLS retrievals. The solution of the unimodal expression is then used in the RMST analysis. In the OE retrieval, the *a priori* profile is also the unimodal log-normal distribution of the stratospheric background aerosols.

The explanation for this feature of their retrieved SAGE II results is a combination of two facts: The first is that the measurements were made at a time when the atmosphere was still showing a significant residue of the volcanic aerosols from the April 1982 El Chichón volcanic eruption.[23] Thus particles with a mean radius greater than the background situation are expected.[24] The second fact is that the aerosol-size distribution information content at SAGE II wavelengths is confined primarily in the radius range from approximately 0.2 to 0.8 μm, as mentioned above. For these reasons, the retrieved SAGE II results in Wang *et al.*[7] generally reflect the charac-

teristics of the volcanic condition of the lower stratosphere at the time of the measurement and are not unrealistic as indicated in Thomason.[10] Furthermore, the derived size distributions in Wang *et al.*[7] were used in the aerosol-extinction analysis by Parameswaran *et al.*[25] Their comparison study showed a reasonable agreement between SAGE II measurements and lidar-converted extinction profiles.

As mentioned in Subsection 3.A., the SAGE III instrument is equipped with three more aerosol channels and covers a wider spectral range than the SAGE II instrument. Therefore it is reasonable to expect that SAGE III can provide better aerosol-size-distribution information than SAGE II. Clearly the four aerosol-extinction measurements from SAGE II cannot be used to derive a bimodal log-normal size distribution without introducing any additional constraints. Furthermore, with three more aerosol channels than SAGE II, the SAGE III measurements are expected to provide stronger constraints to the inverted solutions. To illustrate this point, the simulated aerosol extinctions at SAGE II and SAGE III wavelengths from the observed volcanic-aerosol-size distribution after the Pinatubo eruption (Table 3) are used to retrieve a unimodal log-normal distribution. The retrieved results for SAGE II and SAGE III are compared in Fig. 6. Evidently the SAGE III retrieval is more satisfactory than the SAGE II retrieval. [A much better retrieved SAGE III size distribution for the Pinatubo observation, by use of a bimodal analysis, is shown in Fig. 4(b).] In addition, the error estimates are smaller in the SAGE III than in the SAGE II, indicating stronger retrieval constraints in the SAGE III aerosol observations.

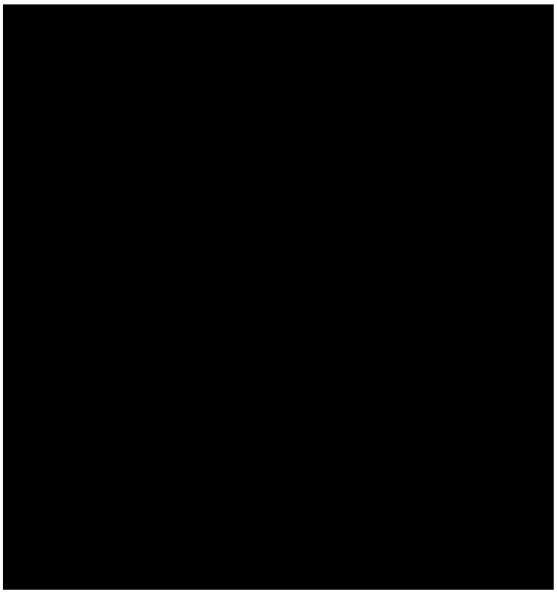

Fig. 6. Comparison of the aerosol-size-distribution retrieval between the four-channel SAGE II and the seven-channel SAGE III aerosol observations. The simulated aerosol extinctions are calculations from the observed Pinatubo aerosol-size distribution. The simulated SAGE II and SAGE III observations are then used to retrieve a unimodal log-normal expression.

As demonstrated in the NLS retrieval presented in Figs. 3 and 4, a bimodal log-normal size distribution can be used as an initial guess to retrieve a bimodal as well as a unimodal log-normal expression. This situation is not quite the same if a unimodal distribution is assumed. The reason for this is that if the true distribution is a bimodal one, the unimodal retrieval is likely to respond favorably to the large mode of the true distribution, as illustrated in Fig. 5. It is, therefore, concluded that a bimodal log-normal size distribution is more preferable for use as an initial guess than a unimodal expression in the NLS analysis.

Finally it is interesting to mention that the true aerosol-size distributions in Figs. 4 and 5 are the same; however, the retrieved RMST results are somewhat different. The cause of this difference is likely due to the fact that the RMST analysis in Fig. 4 begins with a retrieved bimodal analytic expression, whereas the one in Fig. 5 begins with a retrieved unimodal distribution. Note the uncertainty estimates of the retrieval in Figs. 3–5. They tend to show the smallest estimate near a radius of 0.6 μm. The estimates become increasingly larger as the size decreases and also increases, particularly for radii less than approximately 0.2 to 0.4 μm and greater than approximately 1 μm. This feature of the estimated uncertainty reflects the overall characteristics of the size-distribution information content in the SAGE III multiwavelength aerosol extinctions discussed in Section 2.

4. Conclusions

This study investigates the retrieval of aerosol-size distributions from simulated aerosol-extinction measurements at SAGE III wavelengths. Results of the investigation indicate that sufficient information on the aerosol-size distribution is contained in the particle-radius range between approximately 0.1 and 1.5 μm, with the primary information in the range from approximately 0.2 to 1.0 μm. Because the SAGE III instrument provides information on aerosol-extinction coefficients at seven wavelengths between 0.385 and 1.55 μm, a bimodal log-normal size distribution can be inferred. In addition, this study shows that a shape-constraint-free size distribution can be derived by use of the randomized minimization search technique (RMST) and the optimal estimation (OE) theory.

In comparison with the SAGE II sensor, the advanced instrument, SAGE III, will enhance aerosol-size retrieval in many aspects. In addition to the extension of the sensitivity of the measurement to much larger particles, the two additional channels centered at 0.760 and 0.940 μm further strengthen the constraints that are important to the size-distribution retrieval analysis. It is, therefore, expected that the SAGE III instrument will provide better aerosol-size-distribution information in a wider particle radius range than SAGE II.

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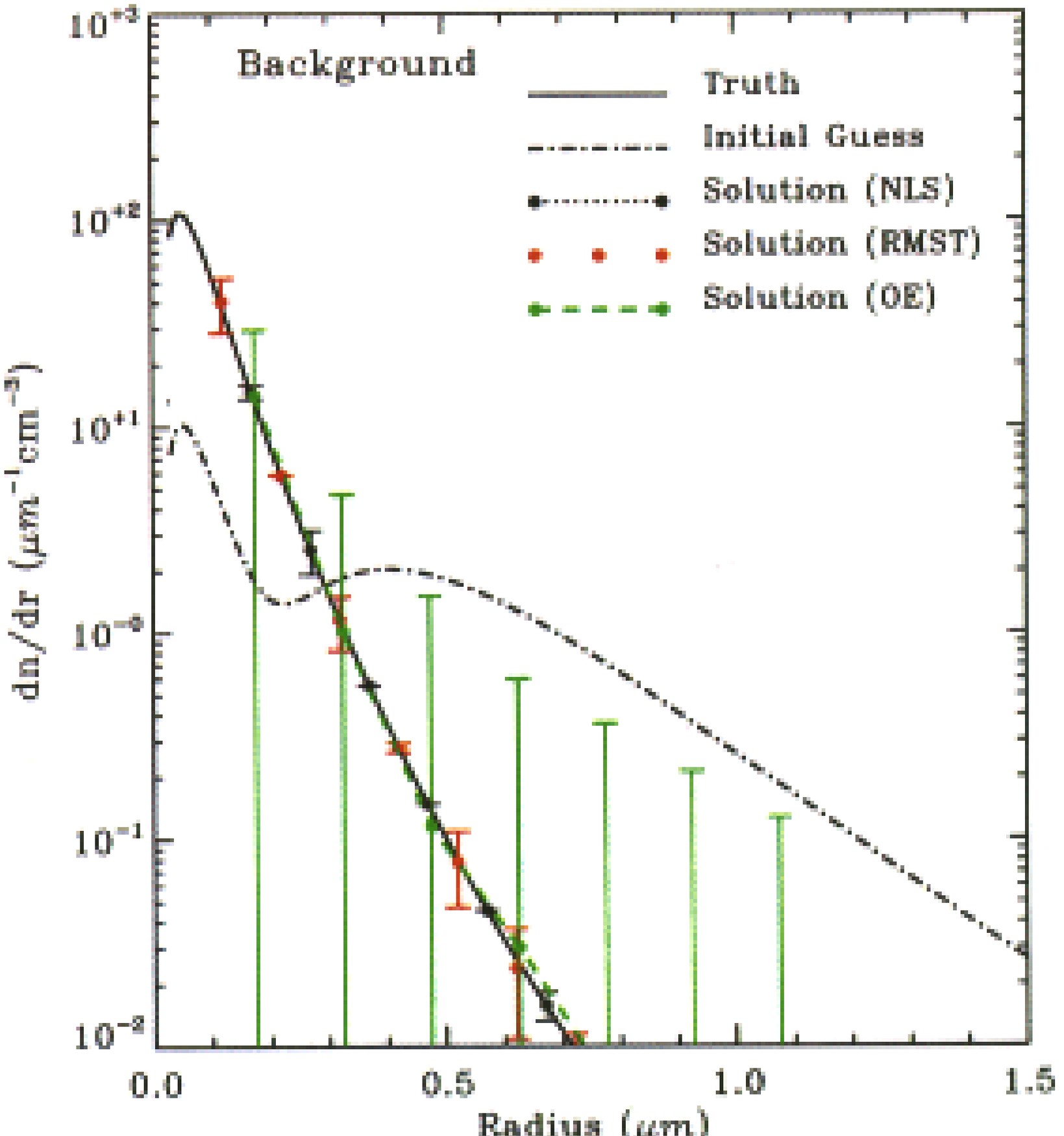
References

1. P. V. Hobbs, ed., *Aerosol-Cloud-Climate Interactions* (Academic, San Diego, 1993).
2. S. Solomon, R. R. Garcia, F. S. Rowland, and D. J. Wuebbles, "On the depletion of Antarctic ozone," Nature **321,** 755–758 (1986).
3. R. Turco, K. Drdla, A. Tabazadeh, and P. Hamill, "Heterogeneous chemistry of polar stratospheric clouds and volcanic aerosols," in *The Role of the Stratosphere in Global Change,* M.-L. Chanin, ed. (Springer-Verlag, Berlin, 1993), pp. 65–134.
4. P.-H. Wang, W. Grant, M. P. McCormick, L. Poole, G. K. Yue, and L. Thomason, "Ozone and water vapor losses in gas-to-particle conversion of volcanic SO_2 in the stratosphere," submitted to Geophys. Res. Lett. (1995).
5. M. P. McCormick, J. M. Zawodny, W. P. Chu, J. W. Baer, J. Guy, and A. Ray, "Stratospheric Aerosol and Gas Experiment III (SAGE III)," in *Sensor Systems for the Early Earth Observing System Platforms,* W. L. Barnes, ed., Proc. Soc. Photo-Opt. Instrum. Eng. **1939,** 137–149 (1993).
6. J. Heintzenberg, H. Müller, H. Quenzel, and E. Thomalla, "Information content of optical data with respect to aerosol properties: numerical studies with a randomized minimization-search-technique inversion algorithm," Appl. Opt. **20,** 1308–1315 (1981).
7. P.-H. Wang, M. P. McCormick, T. J. Swissler, M. T. Osborn, W. H. Fuller, and G. K. Yue, "Inference of stratospheric aerosol composition and size distribution from SAGE II satellite measurements," J. Geophys. Res. **94,** 8435–8446 (1989).
8. M. D. King, "Sensitivity of constrained linear inversions to the selection of the Lagrange multiplier," J. Atmos. Sci. **39,** 1356–1369 (1982).
9. C. Brogniez and J. Lenoble, "Size distribution of stratospheric aerosols from SAGE II multiwavelength extinction," in *Aerosols and Climate,* P. V. Hobbs and M. P. McCormck, eds. (Deepak, Hampton, Va., 1989), pp. 305–312.
10. L. W. Thomason, "A diagnostic stratospheric aerosol size distribution inferred from SAGE II measurements," J. Geophys. Res. **96,** 22501–22508 (1991).
11. N. H. Lin and V. K. Saxena, "Characteristics of antarctic stratospheric aerosols during the 1987 ozone depletion episode based on SAGE II satellite observations," J. Geophys. Res. **97,** 7635–7649 (1992).
12. P.-H. Wang, M. P. McCormick, L. R. Poole, W. P. Chu, G. K. Yue, G. S. Kent, and K. M. Skeens, "Tropical high cloud characteristics derived from SAGE II extinction measurements," Atmos. Res. **34,** 53–83 (1994).
13. C. D. Rodgers, "Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation," Rev. Geophys. Space Phys. **14,** 609–624 (1976).
14. C. D. Rodgers, "Characterization and error analysis of profiles retrieved from remote sounding measurements," J. Geophys. Res. **95,** 5587–5595 (1990).
15. V. R. Oberbeck, E. F. Danielsen, K. G. Snetsinger, and G. V. Ferry, "Effect of the eruption of El Chichón on stratospheric aerosol size and composition," Geophys. Res. Lett. **10,** 1021–1024 (1983).
16. R. G. Pinnick, J. M. Rosen, and D. J. Hofmann, "Stratospheric aerosol measurements. III. Optical model calculations," J. Atmos. Sci. **33,** 304–314 (1976).
17. P. B. Russell, T. J. Swissler, M. P. McCormick, W. Chu, J. M. Livingston, and T. J. Pepin, "Satellite and correlative measurements of the stratospheric aerosol. I. An optical model for data conversion," J. Atmos. Sci. **38,** 1279–1294 (1981).
18. T. Deshler, B. J. Johnson, and W. Rozier, "Balloonborne measurements of Pinatubo aerosol during 1991 and 1992 at 41 °N: vertical profiles, size distribution, and volatility," Geophys. Res. Lett. **20,** 1435–1438 (1993).
19. P. B. Russell, J. M. Livingston, E. G. Dutton, R. F. Pueschel, J. A. Reagan, T. E. DeFoor, M. A. Box, D. Allen, P. Pilewskie, B. M. Herman, S. A. Kinne, and D. J. Hoffmann, "Pinatubo and pre-Pinatubo optical-depth spectra: Mauna Loa measurements, comparisons, inferred particle size distributions, radiative effects and relationship to lidar data," J. Geophys. Res. **98,** 22969–22985 (1993).
20. R. F. Pueschel, P. B. Russell, D. A. Allen, G. V. Ferry, and K. G. Snetsinger, "Physical and optical properties of the Pinatubo volcanic aerosol: aircraft observations with impactors and a sun-tracking photometer," J. Geophys. Res. **99,** 12915–12922 (1994).
21. S. Twomey, *Introduction to the Mathematics of Inversion in Remote Sensing and Indirect Measurements* (Elsevier, New York, 1977).
22. J. D. Spinhirne and M. D. King, "Latitudinal variation of spectral optical thickness and columnar size distribution of the El Chichón stratospheric aerosol layer," J. Geophys. Res. **90,** 10607–10619 (1985).
23. G. S. Kent, P.-H. Wang, M. P. McCormick, and K. M. Skeens, "Multiyear SAGE II measurements of upper tropospheric aerosol characteristics," J. Geophys. Res. **100,** 13875–13899 (1995).
24. J. M. Rosen and D. J. Hofmann, "Optical modelling of stratospheric aerosols: present status," Appl. Opt. **25,** 410–419 (1986).
25. K. Parameswaran, K. O. Rose, B. V. K. Krishna Murthy, M. T. Osborn, and L. R. McMaster, "Comparison of aerosol extinction profiles from lidar and SAGE II data at a tropical station," J. Geophys. Res. **96,** 10861–10866 (1991).


Background
Truth
Initial Guess
Solution (NLS)
Solution (RMST)
Solution (OE)
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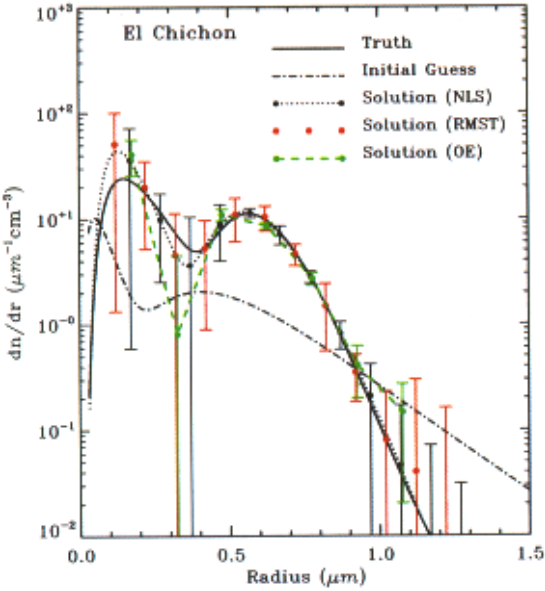
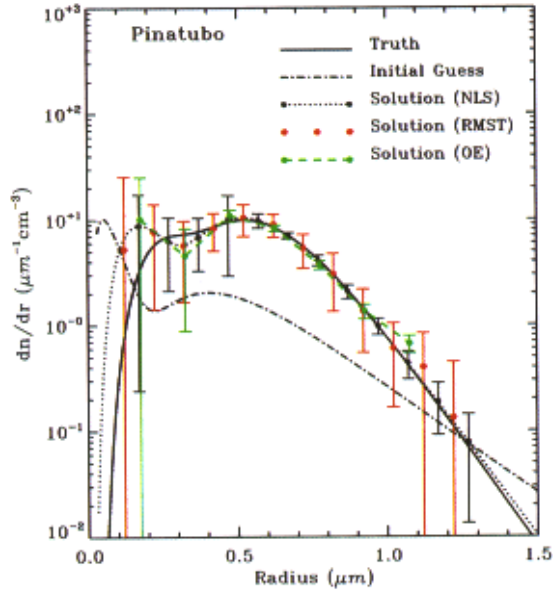
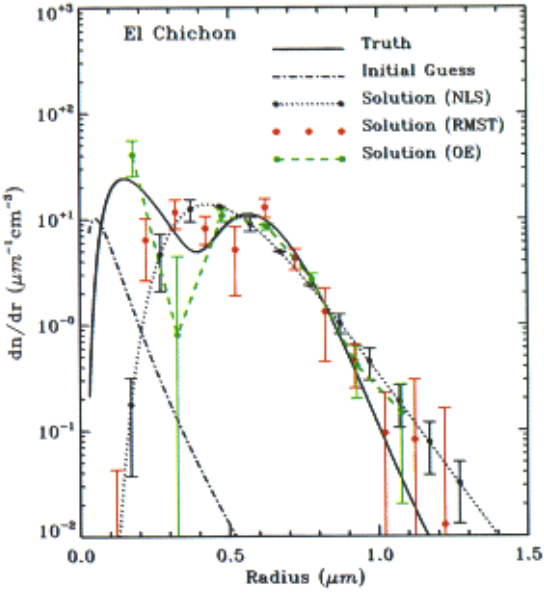
10^{+2}
10^{+1}
10^{+0}
10^{-1}
10^{-2}
dn/dr ($\mu m^{-1} cm^{-3}$)
0.0
0.5
1.0
1.5
Radius (μm)


El Chichon
Truth
Initial Guess
Solution (NLS)
Solution (RMST)
Solution (OE)
dn/dr ($\mu m^{-1} cm^{-3}$)
Radius (μm)


Pinatubo
Truth
Initial Guess
Solution (NLS)
Solution (RMST)
Solution (OE)
dn/dr ($\mu m^{-1} cm^{-3}$)
Radius (μm)


El Chichon
Truth
Initial Guess
Solution (NLS)
Solution (RMST)
Solution (OE)
dn/dr ($\mu m^{-1} cm^{-3}$)
Radius (μm)
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10^{+2}
10^{+1}
10^{-0}
10^{-1}
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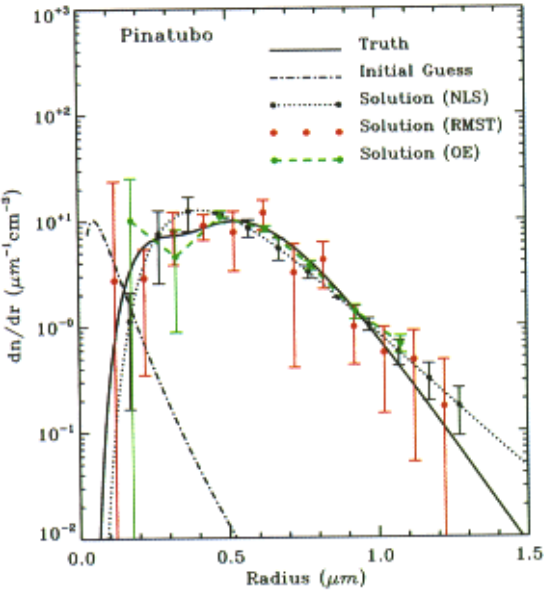
1.0
1.5


Pinatubo
Truth
Initial Guess
Solution (NLS)
Solution (RMST)
Solution (OE)
dn/dr ($\mu m^{-1} cm^{-3}$)
Radius (μm)
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10^{+2}
10^{+1}
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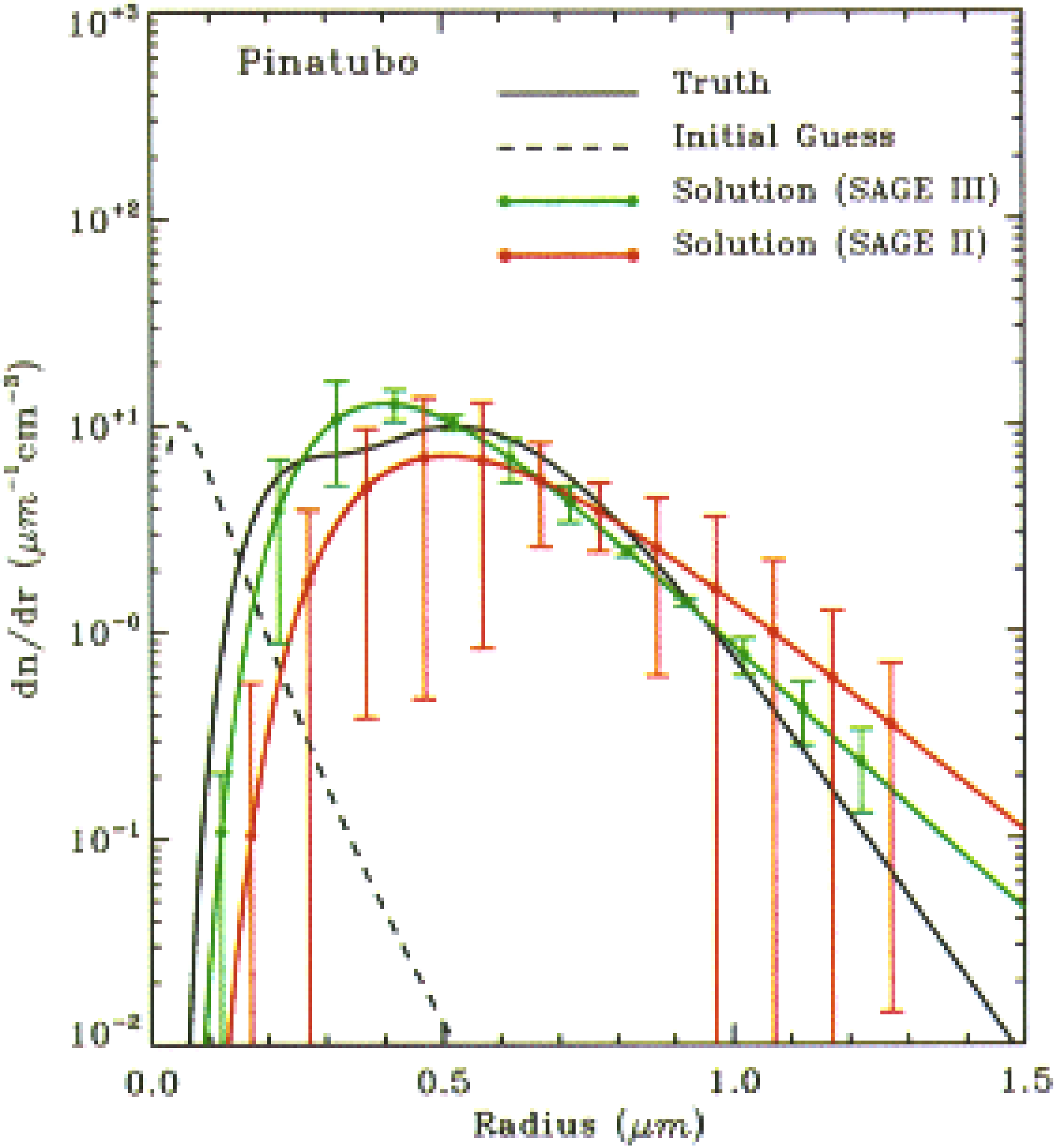
1.0
1.5


Pinatubo
Truth
Initial Guess
Solution (SAGE III)
Solution (SAGE II)
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10^{+2}
10^{+1}
10^{-0}
10^{-1}
10^{-2}
dn/dr ($\mu m^{-1} cm^{-3}$)
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0.5
1.0
1.5
Radius (μm)