RETRIEVAL OF AEROSOL MICROPHYSICAL PROPERTIES FROM THE AERONET PHOTO-POLARIMETRIC MEASUREMENTS

by

Xiaoguang Xu

A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfilment of Requirements

For the Degree of Doctor of Philosophy

Major: Earth & Atmospheric Sciences
(Meteorology/Climatology)

Under the Supervision of Professor Jun Wang

Lincoln, Nebraska

May, 2015

Table of Contents

List of Figures v

List of Tables vi

1 Introduction 1

1.1 Background and Motivation . . . 1

1.1.1 Previous studies on aerosol microphysical retrievals . . . 2

1.1.2 The AERONET measurements . . . 3

1.1.3 Challenges and opportunities . . . 3

1.2 Objectives . . . 3

1.3 Organization . . . 3

2 Model Developments 4

2.1 Introduction . . . 4

2.2 The UNL-VRTM . . . 5

2.2.1 Surface representations . . . 5

2.2.2 Molecular scattering and absorption . . . 5

2.2.3 Aerosol single scattering . . . 5

2.2.4 Radiative transfer . . . 5

2.2.5 Capability of calculating Jacobians . . . 5

2.3 Model Benchmarking and Verifications 5

3 Information Content Analysis **6**

3.1 Introduction 6

3.2 Inversion and Information Theories 6

3.2.1 Inverse problem and error characterization 6

3.3 Experiment Design 6

3.4 Results 6

3.4.1 Error-normalized (EN) Jacobian matrix 6

3.4.2 Information content and retrieval error 6

3.4.2.1 Aerosol PSD 6

3.4.2.2 Refractive indices 6

3.4.2.3 Single scattering albedo 6

3.5 Sensitivity of retrieval error to AOD and fmf 7

3.6 Summary 7

4 Inversion Algorithm **8**

4.1 General sturcture 8

4.2 Combine a priori and smoothness constraints 8

4.3 Statistical optimized inversion 8

4.4 Retrieval Error Characertization 8

4.5 Qaulity Control of Measurements 8

5 Case Demonstrations **9**

5.1 Selected case and the a priori characterization 9

5.2 Fitting Residuals 9

5.3 Retrieved Aerosol Properties 9

5.4 Improvement over Radiance-Only Retrievals 9
5.5 Summary 9

6 Summary and Outlook **10**
6.1 Summary of the Dissertation 10
6.2 Main Conclusions of This Work 10
6.3 Outlook and Future Work 10

A Abbreviations and Acronyms **11**

B Symbols **12**

References **13**

List of Publications **15**

List of Figures

List of Tables

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Atmospheric aerosols play a crucial role in the global climate change. They affect earth energy budget directly by scattering and absorbing solar and terrestrial radiation, and indirectly through altering the cloud formation, lifetime, and radiative properties [*Haywood and Boucher*, 2000; *Ramanathan et al.*, 2001]. However, quantification of these effects in the current climate models is fraught with uncertainties. The global average of aerosol effective radiative forcing were estimated to range from –0.1 to –1.9 Wm^{-2} with the best estimate of –0.9 Wm^{-2} [*Boucher et al.*, 2013], indicating that the cooling effects of aerosol might counteract the warming effects of 1.82±0.19 Wm^{-2} caused by the increase of carbon dioxide since the industrial revolution [*Myhre et al.*, 2013]. The climate effects of aerosol particles depend on their geographical distribution, optical properties, and efficiency as cloud condensation nuclei and ice nuclei. Key quantities pertain to the aerosol optical and cloud-forming properties include particle size distribution (PSD), chemical composition, mixing state, and morphology [Boucher et al., 2013]. While the daily aerosol optical depth (AOD) can be well measured from current satellite and ground-based remote sensing instrumentations [e.g., *Holben et al.*, 1998; *Kaufman et al.*, 2002], the accurate quantification of aerosol ERF is in no small part hindered by our limited knowledge about the aerosol PSD and refractive index (describing chemical composition and mixing state).

To fully understand the role of aerosol particles in the global climate change, further development in observations along with retrieval algorithms for these aerosol microphysical properties from different platforms are thus highly needed [*Mishchenko et al.*, 2004], and the focus of this two-part series study is the characterization of aerosol properties from ground-based passive remote sensing.

1.1.1 Previous studies on aerosol microphysical retrievals

There have been continuous efforts in determining aerosol microphysical properties from ground-based measurements of direct and/or diffuse solar radiation since *Ångström* [1929] first suggested an empirical relationship between the spectral dependency of extinction coefficients and the size of aerosol particles. Over thirty years later, *Curcio* [1961] inferred the aerosol PSD from the spectral particulate extinction coefficients in the visible and near-infrared regions. Soon with the effective numerical inversion technique developed by *Phillips* [1962] and *Twomey* [1963] specifically for error-involved optimization, a number of studies explored the use of either spectral attenuations or scattered radiances (in a small range of scattering angles) to determine the aerosol PSD [*Twomey and Howell*, 1967; *Yamamoto and Tanaka*, 1969; *Dave*, 1971; *Grassl*, 1971; *Herman et al.*, 1971; *King et al.*, 1978]. *Shaw* [1979] and *Nakajima et al.* [1983] were among the first studies that have combined optical scattering measurements with spectral extinctions to recover particle size spectrum. *Kaufman et al.* [1994] suggested useful information contained in the sky radiances of larger scattering angles to retrieve the aerosol scattering phase function and PSD. The first operational retrieval algorithm for aerosol microphysical properties was introduced by Nakajima et al. [1996], when the multi-band automatic sun- and sky-scanning radiometer was deployed in the AErosol RObotic NETwork, or the AERONET [Holben et al., 1994, 1998]. All of above mentioned methods treated aerosol particles as homogeneous spheres and with refractive index assumed a priori, even though the refractive index can highly impact the optical, especially the scattering characteristics [Hansen and Travis, 1974]. Tanaka et al. [1982, 1983] developed an inversion library method to estimate the complex refractive index and PSD simultaneously from measurements of scattered radiances polarized in the perpendicular and parallel directions. Another concept for determining refractive index from both direct and diffuse angular radiances was developed by Wendisch and von Hoyningen-Huene [1994] and Yamasoe et al. [1998], which were based on the fact that sensitivities of scattered radiances to the PSD and those to the refractive index are dominated on different scattering-angular regions. The current AERONET operational inversion algorithm was developed by Dubovik and King [2000], which has heritage from algorithms developed by King et al. [1978] and Nakajima et al. [1983, 1996] but was implemented for simultaneous retrieval of particle size distribution and complex refractive index with sophisticated inclusion of multiple a priori constraints. Dubovik et al. [2002, 2006] further implemented the spheroids in the particle shape consideration for desert dust in the retrieval, and added fractional volume of non-spherical particles to the inversion products.

1.1.2 The AERONET measurements

1.1.3 Challenges and opportunities

1.2 Objectives

1.3 Organization

CHAPTER 2

MODEL DEVELOPMENTS

2.1 Introduction

The radiation fields—radiance and the state of polarization—measured by the remote sensing instruments are the outcome of the interations of solar radiation with various physical processes including the absorption and scattering by atmospheric molecules, aerosols and clouds, as well the reflection and absorption by underlying surface. The radiance and polarization of light at

2.2 The UNL-VRTM

2.2.1 Surface representations

2.2.2 Molecular scattering and absorption

2.2.3 Aerosol single scattering

2.2.4 Radiative transfer

2.2.5 Capability of calculating Jacobians

2.3 Model Benchmarking and Verifications

CHAPTER 3

INFORMATION CONTENT ANALYSIS

3.1 Introduction

3.2 Inversion and Information Theories

3.2.1 Inverse problem and error characterization

3.3 Experiment Design

3.4 Results

3.4.1 Error-normalized (EN) Jacobian matrix

3.4.2 Information content and retrieval error

3.4.2.1 Aerosol PSD

3.4.2.2 Refractive indices

3.4.2.3 Single scattering albedo

To be filled . . .

3.5 Sensitivity of retrieval error to AOD and fmf

To be filled . . .

3.6 Summary

To be filled . . .

CHAPTER 4

INVERSION ALGORITHM

4.1 General sturcture

Basic formulation of inverse problem; sturcture of the algorithm.

4.2 Combine a priori and smoothness constraints

4.3 Statistical optimized inversion

4.4 Retrieval Error Characertization

4.5 Qaulity Control of Measurements

CHAPTER 5

CASE DEMONSTRATIONS

5.1 Selected case and the a priori characterization

5.2 Fitting Residuals

5.3 Retrieved Aerosol Properties

5.4 Improvement over Radiance-Only Retrievals

5.5 Summary

CHAPTER 6

SUMMARY AND OUTLOOK

6.1 Summary of the Dissertation

6.2 Main Conclusions of This Work

6.3 Outlook and Future Work

APPENDIX A

ABBREVIATIONS AND ACRONYMS

APPENDIX B

SYMBOLS

REFERENCES

Boucher, O., et al. (2013), *Clouds and Aerosols. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker T.F., et al. (eds.)]*, p. 571–658, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1.1

Curcio, J. (1961), Evaluation of atmospheric aerosol particle size distribution from scattering measurements in the visible and infrared, *Journal of the Optical Society of America*, *51*(5), 548–551. 1.1.1

Dave, J. V. (1971), Determination of size distribution of spherical polydispersions using scattered radiation data, *Applied Optics*, *10*(9), 2035–2044. 1.1.1

Grassl, H. (1971), Determination of aerosol size distributions from spectral attenuation measurements, *Applied Optics*, *10*(11), 2534–2538. 1.1.1

Haywood, J., and O. Boucher (2000), Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review, *Rev. Geophys.*, *38*(4), 513–543. 1.1

Herman, B. M., S. R. Browning, and J. A. Reagan (1971), Determination of aerosol size distributions from lidar measurements, *Journal of the Atmospheric Sciences*, *28*(5), 763–771. 1.1.1

Holben, B. N., et al. (1998), Aeronet - a federated instrument network and data archive for aerosol characterization, *Remote Sensing of Environment*, *66*(1), 1–16. 1.1

Kaufman, Y. J., A. Gitelson, A. Karnieli, E. Ganor, R. S. Fraser, T. Nakajima, S. Mattoo, and B. N. Holben (1994), Size distribution and scattering phase function of aerosol particles retrieved from sky brightness measurements, *Journal of Geophysical Research: Atmospheres*, *99*(D5), 10,341–10,356.

Kaufman, Y. J., D. Tanre, and O. Boucher (2002), A satellite view of aerosols in the climate system, *Nature*, *419*, 215 – 223. 1.1

King, M. D., D. M. Byrne, B. M. Herman, and J. A. Reagan (1978), Aerosol size distributions obtained by inversions of spectral optical depth measurements, *Journal of the Atmospheric Sciences*, *35*(11), 2153–2167. 1.1.1

Mishchenko, M. I., B. Cairns, J. E. Hansen, L. D. Travis, R. Burg, Y. J. Kaufman, J. Vanderlei Martins, and E. P. Shettle (2004), Monitoring of aerosol forcing of climate from space: analysis of measurement requirements, *Journal of Quantitative Spectroscopy and Radiative Transfer*, *88*(1-3), 149–161. 1.1

Myhre, G., et al. (2013), *Anthropogenic and Natural Radiative Forcing. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker T.F., et al. (eds.)]*, book section 8, p. 659–740, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1.1

Nakajima, T., M. Tanaka, and T. Yamauchi (1983), Retrieval of the optical properties of aerosols from aureole and extinction data, *Applied Optics*, *22*(19), 2951–2959. 1.1.1

Phillips, D. L. (1962), A technique for the numerical solution of certain integral equations of the first kind, *J. ACM*, *9*(1), 84–97. 1.1.1

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld (2001), Aerosols, climate, and the hydrological cycle, *Science*, *294*(5549), 2119–2124. 1.1

Shaw, G. E. (1979), Inversion of optical scattering and spectral extinction measurements to recover aerosol size spectra, *Applied Optics*, *18*(7), 988–993. 1.1.1

Twomey, S. (1963), On the numerical solution of fredholm integral equations of the first kind by the inversion of the linear system produced by quadrature, *J. ACM*, *10*(1), 97–101. 1.1.1

Twomey, S., and H. B. Howell (1967), Some aspects of the optical estimation of microstructure in fog and cloud, *Applied Optics*, *6*(12), 2125–2131. 1.1.1

Yamamoto, G., and M. Tanaka (1969), Determination of aerosol size distribution from spectral attenuation measurements, *Applied Optics*, *8*(2), 447–453. 1.1.1

Ångström, A. (1929), On the atmospheric transmission of sun radiation and on dust in the air, *Geografiska Annaler*, *11*, 156–166. 1.1.1

LIST OF PUBLICATIONS

List my publication here