Journal of Quantitative Spectroscopy & Radiative Transfer 144 (2014) 68–85

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Adjoint methods for adjusting three-dimensional atmosphere and surface properties to fit multi-angle/multi-pixel polarimetric measurements

William Martin [a,*], Brian Cairns [b], Guillaume Bal [a]

[a] Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027, USA
[b] NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA

ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form
27 March 2014
Accepted 28 March 2014
Available online 5 April 2014

Keywords:
Adjoint methods
Three-dimensional vector radiative transfer
Linearization
Remote sensing
Parameter derivatives

ABSTRACT

This paper derives an efficient procedure for using the three-dimensional (3D) vector radiative transfer equation (VRTE) to adjust atmosphere and surface properties and improve their fit with multi-angle/multi-pixel radiometric and polarimetric measurements of scattered sunlight. The proposed adjoint method uses the 3D VRTE to compute the measurement misfit function and the adjoint 3D VRTE to compute its gradient with respect to all unknown parameters. In the remote sensing problems of interest, the scalar-valued misfit function quantifies agreement with data as a function of atmosphere and surface properties, and its gradient guides the search through this parameter space. Remote sensing of the atmosphere and surface in a three-dimensional region may require thousands of unknown parameters and millions of data points. Many approaches would require calls to the 3D VRTE solver in proportion to the number of unknown parameters or measurements. To avoid this issue of scale, we focus on computing the gradient of the misfit function as an alternative to the Jacobian of the measurement operator. The resulting adjoint method provides a way to adjust 3D atmosphere and surface properties with only two calls to the 3D VRTE solver for each spectral channel, regardless of the number of retrieval parameters, measurement view angles or pixels. This gives a procedure for adjusting atmosphere and surface parameters that will scale to the large problems of 3D remote sensing. For certain types of multi-angle/multi-pixel polarimetric measurements, this encourages the development of a new class of three-dimensional retrieval algorithms with more flexible parametrizations of spatial heterogeneity, less reliance on data screening procedures, and improved coverage in terms of the resolved physical processes in the Earth's atmosphere.

1. Introduction

More accurate and complete monitoring of cloud and aerosol properties is needed to reduce uncertainties in both the radiative forcing of climate and feedbacks between the radiative forcing and changes in global temperature that are the result of changes to clouds and their properties [1]. While multi-angle polarimetric measurements and plane parallel retrieval methods provide the capabilities necessary for regions that are horizontally homogeneous [2–4], the retrieval of aerosols in broken cloud fields and near cloud edges remains an open challenge which limits the coverage and accuracy of retrievals [5–7]. Using the three-dimensional (3D) vector radiative transfer equation (VRTE) can address this issue by explicitly accounting for the spatial distribution of solar illumination, scattering material, and polarimetric measurements. In contrast to plane-parallel and spherical models for radiative transfer, the 3D VRTE places no default

* Corresponding author. Tel.: +1 212 678 5567.
E-mail address: wgm2111@columbia.edu (W. Martin).

http://dx.doi.org/10.1016/j.jqsrt.2014.03.030

Nomenclature

Vectors are assigned to bold lowercase letters, matrices are assigned to bold uppercase letters, and integral operators are assigned to script uppercase letters.

Remote sensing problem

n, N	index for unknowns and total number
m, M	index for measurements and total number
L	number of wavelengths
$\boldsymbol{a}, a^n$	vector of unknowns and elements
$\hat{\boldsymbol{y}}, \hat{y}^m$	measurements vector and elements
$\boldsymbol{y}(\boldsymbol{a}), y^m(\boldsymbol{a})$	measurement model vector and elements
$\Phi(\boldsymbol{a})$	misfit function

Domain

$\boldsymbol{x}$	position in space
$h(\boldsymbol{x})$	signed distance to boundary
$\nabla h(\boldsymbol{x})$	outward pointing normal
$\boldsymbol{v}$	direction unit vector
$\mathbb{S}^2$	unit sphere
D	spatial domain
∂D	spatial domain boundary
$D \times \mathbb{S}^2$	internal set
Γ_+	outgoing set
Γ_-	incoming set

Single scattering

$\sigma(\boldsymbol{x}; \boldsymbol{a})$	volume extinction coefficient
$\boldsymbol{Z}(\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{v}'; \boldsymbol{a})$	volume scattering kernel
$\boldsymbol{R}(\boldsymbol{x}, \boldsymbol{v}_-, \boldsymbol{v}_+; \boldsymbol{a})$	surface reflection kernel

Forward vector radiative transfer

$\boldsymbol{u}$	Stokes vector solution
$\boldsymbol{f}_\odot$	internal light source (internal forward source)
$\boldsymbol{g}_\odot$	solar illumination (incoming forward source)
$\Delta \boldsymbol{f}^n_\odot$	internal source for parameter derivatives
$\Delta \boldsymbol{g}^n_\odot$	incoming source for parameter derivatives
$\mathcal{Z}$	scattering operator
$\mathcal{R}$	reflection operator
$\mathcal{U}_{\boldsymbol{a}}$	forward solution operator

Adjoint vector radiative transfer

$\boldsymbol{w}$	adjoint Stokes vector solution
$\boldsymbol{p}^m_\odot$	polarization analyzer (internal adjoint source)
$\boldsymbol{q}^m_\odot$	polarization analyzer (outgoing adjoint source)
$\Delta \boldsymbol{p}_\odot$	internal source vector for misfit gradient
$\Delta \boldsymbol{q}_\odot$	outgoing source vector for misfit gradient
$\mathcal{Z}^*$	adjoint of scattering operator
$\mathcal{R}^*$	adjoint of reflection operator
$\mathcal{U}^*_{\boldsymbol{a}}$	adjoint solution operator

Forward integral equations

$\mathcal{T}_{00}$	forward streaming operator (internal-to-internal)
$\mathcal{T}_{-0}$	forward streaming operator (incoming-to-internal)
$\mathcal{T}_{0+}$	forward streaming operator (internal-to-outgoing)
$\mathcal{T}_{-+}$	forward streaming operator (incoming-to-outgoing)
$\boldsymbol{f}$	internal solution to the forward integral equations
$\boldsymbol{g}$	incoming solution to the forward integral equations

Adjoint integral equations

$\mathcal{T}^*_{00}$	adjoint streaming operator (internal-to-internal)
$\mathcal{T}^*_{-0}$	adjoint streaming operator (internal-to-incoming)
$\mathcal{T}^*_{0+}$	adjoint streaming operator (outgoing-to-internal)
$\mathcal{T}^*_{-+}$	adjoint streaming operator (outgoing-to-incoming)
$\boldsymbol{p}$	internal solution to the adjoint integral equations
$\boldsymbol{q}$	outgoing solution to the adjoint integral equations

Subscripts

$\odot$	indicates a source vector, i.e. right-hand side
0	defined on or related to the internal set
$+$	defined on or related to the outgoing set
$-$	defined on or related to the incoming set

Superscripts

T	transpose of a vector or matrix
$*$	adjoint of an operator
$'$, $''$	integration variables

restrictions on the spatial variability of the atmosphere and surface [8]. Work to extend coverage with 3D methods has shown promise for determining average cloud optical thickness [9] and cloud top height [10]. However, as a side effect of the increased flexibility, the 3D VRTE leads to retrieval problems with many more unknown parameters and multi-pixel measurement constraints. A significant concern is therefore the extent to which a proposed algorithm scales “gracefully” to large problems. The objective of this work is to formulate an adjoint method for the 3D VRTE which maintains the scalability required for the application to atmospheric remote sensing problems.