MULTI-ANGLE AEROSOL RETRIEVALS WITHOUT LOOKUP TABLES: A FEASIBILITY STUDY FOR MISR

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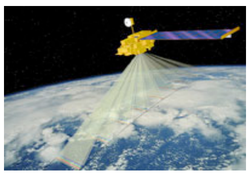
Motivation

Currently, many satellite-based aerosol retrievals make use of look-up tables (LUTs) containing pre-computed solutions to the radiative transfer (RT) equation. The benefit of this strategy is the avoidance of expensive runtime calculations, but its main drawback is that the LUTs discretize what is inherently a continuous solution space, and LUTs fundamentally restrict the size of the solution space. The operational retrieval algorithm for the Multi-angle Imaging SpectroRadiometer (MISR) [1], for example, compares up to 36 radiance observations to a set of 74 aerosol mixtures, each composed of particle models having prescribed optical properties and size distributions. In a recent "blind" study [2] comparing the performance of several satellite retrieval algorithms on simulated data over a black surface, the operational MISR algorithm performed reasonably well in recovering the "true" aerosol optical depths (AODs), but because the simulated aerosol model was not contained by the MISR LUT, the **retrieved AODs were biased low by about 14%**. This led us to investigate the following **question:**

Can the MISR retrievals be improved if a more robust means of expanding the allowable solution space is employed, or is the retrieval bias due to an inherent lack of information content in the simulated radiances?

About the Multiangle Imaging SpectroRadiometer (MISR)



- Onboard the EOS Terra Satellite
- Operational since early 2000
- Measures 36 top-of-atmosphere radiances for each location, as combinations of
  - 9 view angles (0.0°, ±26.1°, ±46.1°, ±60.0°, and ±70.5°)
  - 4 spectral bands in the visible to NIR range, with centers at 446, 558, 672, and 867 nm

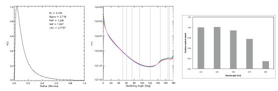
    (For this study we use 443, 560, 670, and 865 nm as the 'MISR wavelengths,' following the synthetic data provided for the original study in ref. [2])
- Footprint: 275 x 275 m^2 to 1.1 x 1.1 km^2

Forward Calculation

☑ **Aerosol Model[2]:** As in the original study, the aerosol is modeled as a spherical non-absorbing particle, with a real refractive index n_r of 1.38. Letting r denote particle radius and N the total number of particles per unit volume, the particle size distribution is log-normal:

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

The median radius r_m is set to 0.1μm and the distribution width σ to 1.



Left: the log-normal particle size distribution; Middle: aerosol phase functions for the four MISR bands, with vertical lines showing the 9 scattering angles; Right: Spectral AODs relative to AOD at 412nm.

☑ **Scene:** The atmosphere is modeled as two distinct plane-parallel, homogeneous layers: Rayleigh directly above aerosol. The surface is assumed black. The solar zenith angle is fixed at 60°. The synthetic measurements are taken in the principal plane, maximizing the range of MISR scattering angles for a given sun angle, however this geometry is not actually observed by MISR in orbit on the Terra satellite.

☑ **Calculating TOA radiances:** For each of the 4 MISR wavelengths λ, the following steps are taken:

1) Mie theory is used to calculate the single-scattering phase function.
2) Given τ_{550}, calculate $\tau_\lambda = \tau_{550}\, \kappa_\lambda / \kappa_{550}$, where κ_λ is the band's extinction cross section.
3) The radiative transfer equation is solved using a Successive Orders of Scattering code [3], generating TOA radiances for each of the 9 MISR view angles.
4) Convert to bidirectional reflectance factors (BRF).

Synthetic Data

☑ We make the following choices in order to simplify the question at hand:
- The same forward calculation as described above is used for both the synthetic data and the inversion.
- No noise is added.

☑ Following the original study in ref. [2], we consider **16 cases**, differing only by AOD. The 16 cases relate to the following AODs at 412nm:

case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
τ_{412}	0	0.01	0.02	0.03	0.04	0.05	0.1	0.2	0.3	0.4	0.5	1	2	3	4	5

Retrieval Approach

☑ We seek to minimize the following **least-squares cost function**:

$$C(\mathbf{x}) = \sum_{j=1}^{36}\left[R_j^{model}(\mathbf{x}) - R_j^{obs}\right]^2$$

Here R_j represents the j^{th} TOA BRF, and $\mathbf{x}$ is a vector for the five parameters listed in the table on the right.

Parameter	Symbol	Min	Max	True	x_0
Median radius	r_m	0.02	1	0.1	rand
Distribution width	σ	1.1	3	2.72	rand
Real refractive index	n_r	1.3	1.7	1.38	rand
Imaginary refractive index	n_i	0	0.2	0	0
Reference AOD	τ_{550}	1e-4	7	0 - 5	1e-3

☑ The third and fourth columns of the table show the **box constraints** we impose on the solution space, chosen to represent the plausible range of aerosols found over the Earth.

☑ We use a **Levenberg-Marquardt algorithm** [4,5]. Given an initial guess, $\mathbf{x_0}$, the algorithm generates a series of improved estimates $\mathbf{x_1}, \mathbf{x_2}, \ldots$ which (hopefully) converge to the solution. At each iteration, the next step is calculated by solving the following linear system:

$$\left(\mathbf{J}^T\mathbf{J} + \mu_k \mathbf{I}\right)\left(\mathbf{x}_{k+1} - \mathbf{x}_k\right) = -\mathbf{J}^T\mathbf{C}(\mathbf{x}_k)$$

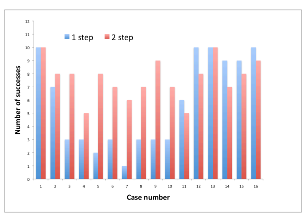
where $\mathbf{J}$ is the Jacobian of the cost function at $\mathbf{x}_k$, $\mathbf{I}$ is the identity matrix, and μ_k is called the *damping parameter*. Levenberg-Marquardt behaves as a combination of the Gauss-Newton and Gradient Descent methods; when far from the solution, it acts like Gradient Descent, whereas near the solution, the direction is more similar to that of Gauss-Newton.

☑ Although the algorithm can terminate for several reasons, including the residual, gradient or step-length dropping below specified thresholds, our sole **convergence criterion** is the residual dropping below 1e-6.

☑ Because the algorithm is sensitive to initial conditions, we use **10 different starting points** for the retrievals, chosen as shown in the last column in the table above. We initialize n_i and τ_{550} to small values to avoid degeneracy which can result in cases with extremely low single-scattering albedo.

☑ We tried two different retrieval schemes: a simple **one-step** optimization, and a **two-step** approach. In the two-step approach, the first step consists of a few iterations using a single-scattering approximation, the results of which become the initial guess for the full multiple-scattering retrieval.

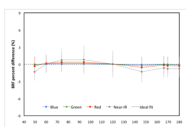
Results[6]



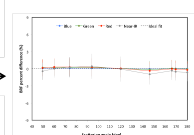
☑ Number of retrieval successes (i.e., convergence with residuals below the specified threshold of 1e-6) out of 10 initialization trials as a function of case number, comparing the 1-step and 2-step algorithms.

☑ Retrieval statistics averaged over all successful retrievals per case, then averaged over all cases (each increasing by roughly 50% from low AOD to high AOD). Calculations were done with an Intel Xeon X5450 3.0 GHz Processor, 16G RAM.

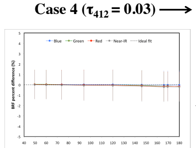
	# Cost Function Evaluations	Runtime (min)	# Iterations
1-STEP	138	23	14
2-STEP	186	27	19



Case 2 (τ_{412} = 0.01)

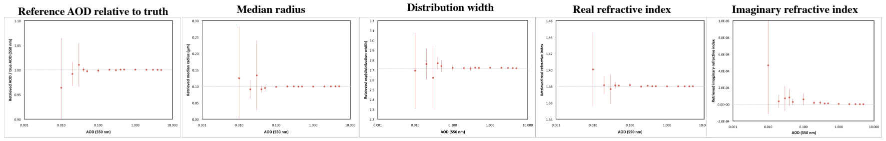


Case 4 (τ_{412} = 0.03)



Case 12 (τ_{412} = 1.0)

☑ BRF differences (%) in each of the 36 channels for the worst successful retrievals in 3 different cases using the 2-step approach. Error bars represent MISR channel-to-channel measurement uncertainty for 1.1 x 1.1 km^2 spatial resolution [7].



☑ Mean value of retrieved parameters averaged over the initialization trials for the successfully converged results using the 2-step approach in cases 2-16 (case 1 is omitted as the AOD in this case is 0, hence the retrieved aerosol parameters are meaningless). Error bars indicate one standard deviation. The horizontal lines show the true values (or in the case of AOD, the ideal ratio of 1.0).

Conclusions

☑ For the idealized scenario posed in the original study [2], retrievals based on least-squares optimization of continuously varying aerosol parameters yield **far superior results** compared to those obtained with a LUT. Undoubtedly, using a LUT containing the "correct" aerosol model would yield excellent results as well, but the advantage of the optimization approach is that it eliminates the need to discretely predefine the solution space and allows the space to be explored more broadly.

☑ The study in ref. [2] found that the LUT-based MISR retrieval ranked higher than many other approaches, but was surpassed in accuracy by an optimization-based retrieval using simulated multiangle, spectropolarimetric observations. We conclude here that **limitations of the LUT used in the study, and not the lack of polarimetric information, account for this result**. Other observational and theoretical studies have clearly shown that additional polarimetric information provides added value to aerosol retrievals. Our findings suggest, however, that **multiangle spectral intensity-only retrievals that rely solely on discretized LUTs may not take best advantage of the full information content of the observations**.

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