Importance of Polarization for Remote Sensing of the Earth's Atmosphere

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Radiative Transfer & Aerosol Modelling

Radiative transfer (VLIDORT v.2.5), surface (BRDF supplement) and aerosol (Linearized T-matrix and Mie) codes have been provided by Dr. Robert Spurr, RT SOLUTIONS, Inc., Cambridge, MA 02138, USA, http://www.rtslidort.com/index.html.

The codes are written in the form of subroutines, each of which is designated to solve a specific set of tasks. These subroutines can be easily incorporated into any other code or combined in the way preferred by the user.

Input file

BRDF Supplement
- Scalar & Vector BRDF (Bidirectional Reflectance Distribution Function) models
- Written in F90 & F77

+

Atmospheric model
- Standard set of atmospheric subroutines in F90

+

Input file

VLIDORT 2.5
- Linearized RT (radiance, profile & column Jacobians w.r.t. atmospheric & surface variables)
- Scalar (no polarization) & vector (with polarization) modes
- Pseudo-spherical geometry
- Spectrum from UV to thermal IR
- Written in F90 & F77

+

Input file

Linearized T-matrix & Mie
- Optical properties of spherical & non-spherical particles (extinction & scattering X-sections, scattering matrix)
- Jacobians of optical properties w.r.t. particle refractive index, size distribution & shape)
- Written in F90

Output files
- Profile or column Jacobians w.r.t. chosen variables
- Radiance on top-of-atmosphere or at any layer inside the atmosphere

Retrieval Algorithm
- Retrieval theory on the basis of Rodger's OEM (e.g., written in MATLAB)

References

- Spurr R, User's Guide, VLIDORT, version 2.5, RT Solutions, Inc., USA, March 2011.
- Spurr R, Wang J, Zeng J, & Mishchenko MI. VLIDORT: Linearized T-matrix and Mie scattering computations. JQSRT 2012; 113: 425-439. (The T-matrix formulation is based on the NASA GISS F77 code developed in the 1990s).
- Rodgers S. Inverse methods for atmospheric sounding: theory and practice. World Scientific, Series on atmospheric, oceanic and planetary physics, 2000; 2.

Polarization Correction Database

Scientific Content

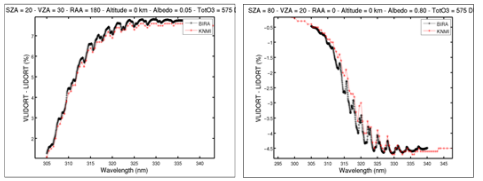
- Molecular atmosphere
- O_3 concentration = {0.0 DU; 125.0 – 575.0 DU with the step of 50.0 DU}
- O_3 X-sections extracted from *Malicet et al., 'Ozone UV Spectroscopy. II. Absorption Cross-sections and Temperature Dependence.' Journal of Atmospheric Chemistry 1995; 21:263-273.*
- SZA = {0.0º – 85.0º, step of 5.0º}; VZA = {0.0º – 85.0º, step of 5.0º}; AZ = {0.0º – 180.0º, step of 30.0º}
- Lambertian surface with α = {0.0 – 1.0, step of 0.05}
- Elevation above the sea level H = {0.0, 5.51, 10.32, 14.71} km
- Spectrum range from 305.0 to 340.0 nm with a spectral resolution of 0.15 nm
- Output: normalized vector & scalar radiance
- RT software: VLIDORT v.2.5 F77 (Use of the code's ability to process a number of geometries at once → Significant time saving!)

Remarks

Control for database creation and further research involving its use for O_3 retrieval have been carried out by C. Lerot (Christophe.Lerot@aeronomie.be)

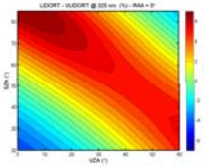
Comparison between the Databases produced by BIRA-IASB and KNMI

- KNMI Database was created at the Royal Nederlands Meteorological Institute.
- Slight differences are attributed to the difference of Rayleigh optical depth modelling.



Effects of Polarization

If polarization is neglected, the relative error, i.e., (VLIDORT – LIDORT)*100% / VLIDORT, can be more than 6% for a molecular atmosphere (depending on the geometry).



Testing of VLIDORT against Coulson's Tabulated Values

Coulson's tabulated values represent the accurate calculations of the solar radiation reflected and transmitted by a plane-parallel, non-absorbing molecular atmosphere in accordance with Rayleigh's law (Coulson KL, Dave JV, & Zekera Z. *Tables related to radiation emerging from a planetary atmosphere with a Rayleigh scattering.* University of California Press, 1960).

Rayleigh OD = 0.25
SZA = 53.1301°, cos(SZA) = 0.6
Relative AZ = 90.0°
PS - "pseudo-spherical"
Lambertian surface α = 0.25

	COULSON			VLIDORT			Difference, %		
VZA	I	Q	U	I	Q	U	I	Q	U
0.0000	0.17967	-0.03513	0.00000	0.17967	-0.03513	0.00000	0.000	0.000	0.000
11.4783	0.17914	-0.02618	0.00955	0.17914	-0.02619	-0.00955	0.000	-0.038	0.000
16.2682	0.17962	-0.02625	0.01225	0.17963	-0.02625	-0.01225	-0.006	0.000	0.000
23.0739	0.17935	-0.02641	0.01780	0.17935	-0.02642	-0.01780	-0.006	-0.038	0.000
32.8599	0.18117	-0.02689	0.02667	0.18118	-0.02690	-0.02667	-0.006	-0.037	0.000
43.9455	0.19810	-0.02811	0.03893	0.19811	-0.02811	-0.03893	0.000	0.000	0.000
50.2882	0.21946	-0.02936	0.04758	0.21946	-0.02936	-0.04758	0.000	0.000	0.000
58.6677	0.25136	-0.03221	0.06259	0.25136	-0.03222	-0.06258	0.000	-0.031	0.016
66.4218	0.29473	-0.03690	0.08209	0.29473	-0.03691	-0.08209	0.000	-0.027	0.000
71.3371	0.32766	-0.04169	0.09941	0.32766	-0.04169	-0.09941	0.000	0.000	0.000
73.7398	0.34568	-0.04481	0.11004	0.34568	-0.04482	-0.11004	0.000	-0.022	0.000
78.4638	0.38233	-0.05313	0.13695	0.38233	-0.05313	-0.13695	0.000	0.000	0.000
80.7931	0.40112	-0.05955	0.15400	0.40112	-0.05956	-0.15400	0.000	-0.017	0.000
84.2688	0.42987	-0.06799	0.18387	0.42987	-0.06800	-0.18387	0.000	-0.015	0.000
86.5682	0.44925	-0.07333	0.20283	0.44929	-0.07333	-0.20283	0.000	0.000	0.000
88.8540	0.46868	-0.07410	0.21959	0.46868	-0.07409	-0.21958	0.000	0.013	0.005

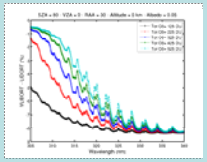
Impact of Polarization on the Product (O_3 and Surface Albedo Retrievals)

GODFIT (GOME-type direct fitting)

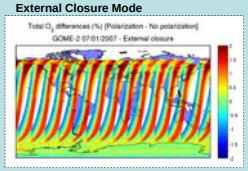
Internal Closure Mode
- Surface albedo is retrieved together with the total O_3, using the absolute values of the measured reflectance.

External Closure Mode
- Surface albedo from climatology
- Only the differential structures in the measured reflectance are used to measure the total O3 column.

Dependence on the O_3 concentration

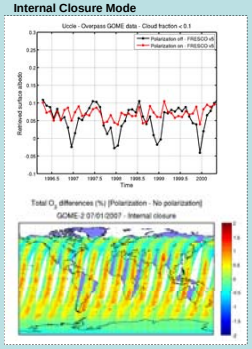


External Closure Mode



*GOME: **G**lobal **O**zone **M**onitoring **E**xperiment

Internal Closure Mode



Polarization in an Aerosol Atmosphere

Study Case (Mineral Aerosol over Ocean & Desert)

The study site was selected on the basis of information provided by L. Clarisse et al. (Article 'Retrieving radius, concentration, optical depth, and mass of different types of aerosols from high-resolution infrared nadir spectra', Applied Optics 2010; 49: 3713-3722): "*MODIS and CALIPSO data on 21 June 2009 show a large dust plume off the West Coast of Mauritania and Senegal at an altitude of around 5 km*".

AQUA-MODIS image (RGB, 2000 m): courtesy of AERONET (MODIS - **Mo**derate **R**esolution **I**maging **S**pectroradiometer)

Research Strategy

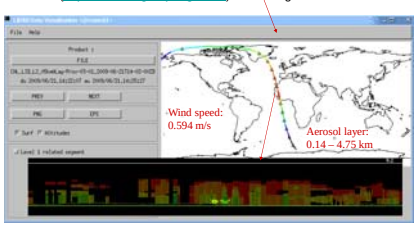
1) **Goal:** to retrieve aerosol parameters (effective radius, real and imaginary refractive indices, i.e., r_{eff}, r_n & r_i) from the PARASOL data.
2) **A-priori Information:** to use AERONET aerosol data (collected at 9:25h & 16:57h) as two a-priori sets for the OEM retrieval method.
3) **Planned retrieval:** to retrieve r_{eff} at λ = 865 nm, at which r_n and r_i do not change much during the day; then to use the retrieved r_{eff} to retrieve r_n and r_i at λ = 490 nm.
4) **Temporary advantages:** λ = {490; 865} nm are in the atmospheric windows → no need to model absorption by H_2O, O_3, CO_2, O_2, N_2O & CH_4.
5) **Other parameters needed for modeling:** Aerosol layer boundaries are extracted from the CALIOP data.

CALIOP Measurements for the Study Case

(**C**loud-**A**erosol **Li**dar with **O**rthogonal **P**olarization)

General information (http://www-calipso.larc.nasa.gov/):
- 2-wavelength (532 & 1064 nm) polarization sensitive lidar
- Installed on-board of the CALIPSO satellite (**C**loud-**A**erosol **Li**dar and **I**nfrared **P**athfinder **S**atellite **O**bservation), which is part of the A-train, launched on April 28, 2006
- Product of interest here: Aerosol vertical distribution & wind speed
- Vertical resolution: 30-60 m; horizontal resolution: 333 m

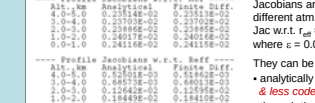
Data tools:
- VISU-CALIOP, developed by B. Six (CGTD-ICARE) to visualize several CALIOP data product with a graphic interface (http://www.icare.univ-lille1.fr/tools/)
- HDFView (http://www.hdfgroup.org/tools/) for reading HDF4 & HDF5 files



Preliminary Results

Atmospheric polarization has no significant effect at 865 nm. The surface is essentially non-Lambertian. It has been simulated with the help of Hapke's model* with the total surface albedo of α = 0.42.

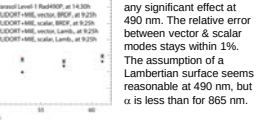
* B. Hapke, Bidirectional reflectance spectroscopy: 1. Theory, JGA, 86, 3039-3054, 1981.



Jacobians are radiance derivative w.r.t. different atm./surface parameters, e.g., Jac w.r.t. r_{eff} = (Rad(r_{eff}+ε)- Rad(r_{eff}))/ ε, where ε = 0.001.

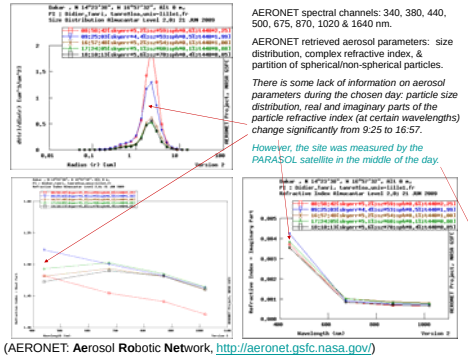
They can be calculated:
- analytically → *significant save of time & less code lines*;
- through the FD (finite difference) method (use of the formula above).

FD is used here to validate Jacobians calculated analytically with the help of VLIDORT and Linearized Mie codes.



Polarization does not have any significant effect at 490 nm. The relative error between vector & scalar modes stays within 1%. The assumption of a Lambertian surface seems reasonable at 490 nm, but α is less than for 865 nm.

AERONET Data for the Study Case



AERONET spectral channels: 340, 380, 440, 500, 675, 870, 1020 & 1640 nm.

AERONET retrieved aerosol parameters: size distribution, complex refractive index, & partition of spherical/non-spherical particles.

There is some lack of information on aerosol parameters during the chosen day: particle size distribution, real and imaginary parts of the particle refractive index (at certain wavelengths) change significantly from 9:25 to 16:57.

However, the site was measured by the PARASOL satellite in the middle of the day.

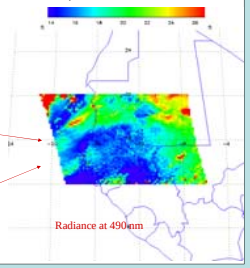
(AERONET: **Ae**rosol **Ro**botic **Net**work, http://aeronet.gsfc.nasa.gov/)

PARASOL Measurements for the Study Case

(**P**olarization & **A**nisotropy of **R**eflectances for **A**tmospheric **S**ciences coupled with **O**bservations from a **Li**dar)

General information (http://smsc.cnes.fr/PARASOL/index.htm):
- PARASOL is part of the A-train constellation; it was launched on December 18 2004.
- It carries the POLDER instrument (**Pol**arization and **D**irectionality of the **E**arth's **R**eflectances).
- 9 spectral bands including 3 polarized bands, namely, 490, 670 and 865 nm
- Level 1 product is normalized radiance (max radiance * PI / solar irradiance).
- Multidirectional acquisition (up to 16 geometries)
- Pixel resolution is close to 6 km² at nadir.

Data tools (http://www.icare.univ-lille1.fr/tools/):
- PARASOLASCII, developed by F. Ducos (ICARE - LOA) to display the data from PARASOL binary files in plain text
- ANAPOL, developed by F.-M. Bréon & M.-P. Moine (LSCE) to visualize and analyze PARASOL & POLDER data through a graphic interface



On 21/06/2009 PARASOL collected data over the Dakar AERONET site from 14:07 to 14:50.

P3L1TBG1104169KD_n20_10_N12_10_w021_80_E012_40
P3L1TBG1104169KL_n20_10_N12_10_w021_80_E012_40

Acknowledgements to:

- STCE (**S**olar **T**erristrial **C**entre of **E**xcellence, Belgium) for funding the 'Radiative Transfer' project (PI M. De Mazière).
- R. Spurr for providing the VLIDORT and Linearized Mie & T-matrix packages.
- F. Ducos, F.-M. Bréon, M.-P. Moine, & B. Six for providing auxiliary tools for working with CALIOP and PARASOL data.
- The ICARE Thematic Center and CNES (National Centre for Space Studies, France) for providing CALIOP and PARASOL data products.

Remarks (in regards to the disagreement with the abstract):

- We have decided to use the Linearized Mie & T-matrix codes (available since 5/04/2012) instead of T-matrix & Mie developed by Dr. M. Mishchenko, as the linearized codes allow us to calculate Jacobians analytically.
- We have decided to use PARASOL (a.k.a. POLDER-3) data as they have much more extensive time and space coverage than POLDER-(2) data.