Limb Scattering Radiative Transfer Model Development in Support of the Ozone Mapping and Profiler Suite (OMPS) Limb Profiler Mission

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7th Atmospheric Limb Conference, June 17-19, 2013, Bremen, Germany

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Abstract

The Gauss-Seidel Limb Scattering (GSLS) radiative transfer (RT) model has been tested through comparison with several other limb RT models, including the Siro, MCC++, CDIPI, LIMBTRAN, and SASKTRAN. To address deficiencies in the GSLS radiance calculations revealed in earlier comparisons, several recent changes have been added that improve the accuracy and flexibility of the GSLS model, including:

1. Introduction of variable atmospheric and surface properties along the limb line of sight.
2. Improved treatment of the variation of the extinction coefficient within atmospheric layers.
3. Re-introduction of the ability to simulate vector (polarized) radiances.
4. Addition of the ability to model multiple aerosol types within the model atmosphere.

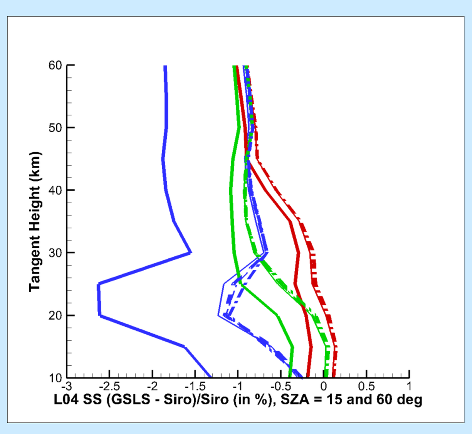
These model improvements are verified by comparison to standard radiance tables, demonstrating significant improvement in cases for which previous versions of the model performed poorly. The GSLS model is imbedded in the retrieval algorithm used to process data from the Ozone Mapping and Profiler Suite (OMPS) Limb Profiler, which was recently launched on the Suomi NPP satellite. The significance of the GSLS RT model improvements for the OMPS LP retrievals will be illustrated by several examples.

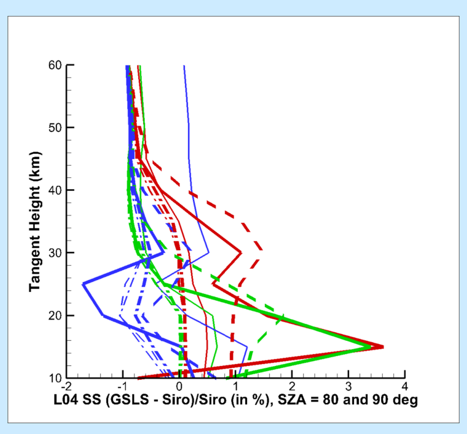
Optical Path Length Improvement

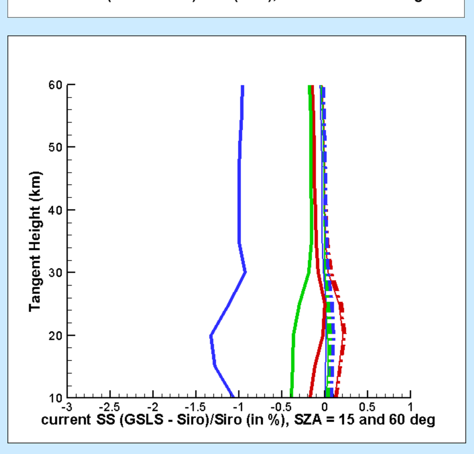
A previous radiance comparison study[1] (called *L04* herein) notes a bias in the GSLS single-scattered (SS) radiances relative to the SS radiances computed by the Siro[2] model. This bias arises from the approximation used to calculate the limb optical path length τ through a layer, based on the layer geometric path length *s* and the extinction coefficients at layer top (β_t) and layer bottom (β_b):

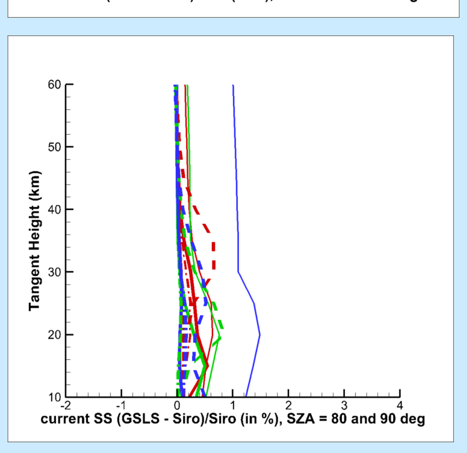
- **L04 GSLS:** $\tau = s * (\beta_t + \beta_b)/2$
- **Siro:** $\tau = \int \beta\, ds$

The L04 GSLS model used the average β within each layer (except the tangent layer), while Siro explicitly integrates β along the path (treating β as a linear function of altitude within each layer).







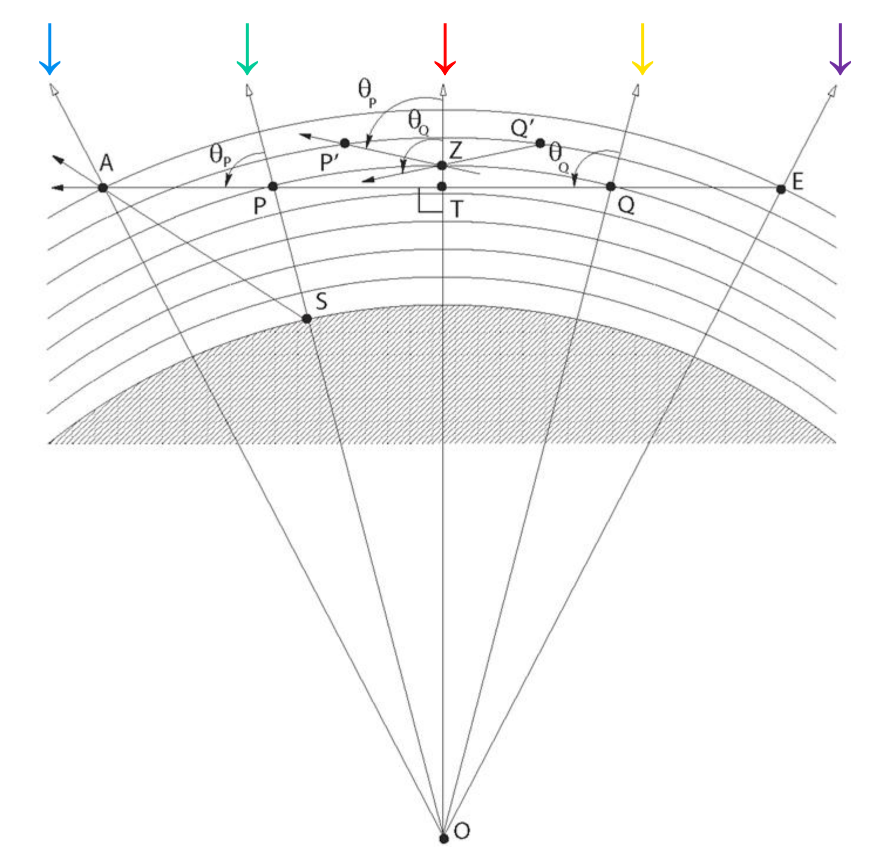


SS Radiance Comparison

The top row above compares Siro SS radiances to GSLS SS radiances, using the L04 method to calculate τ. (These comparisons are shown in a different format in Figs. 6-8 of *reference 1*). In the bottom row, the Siro method is instead used to calculate τ in the current GSLS model, greatly reducing the SS radiance difference from Siro.

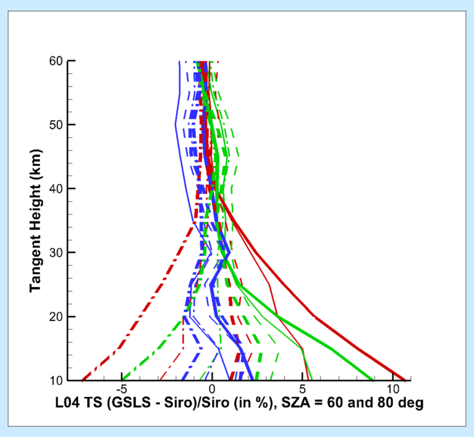
- Comparisons are for 325, 345 and 600 nm.
- The left column corresponds to solar zenith angle (*SZA*) = 15° (*thinner lines*) and 60° (*thicker lines*), while the right column shows *SZA* = 80° (*thinner lines*) and 90° (*thicker lines*).
- *Solid lines* represent solar azimuth angle (*SAZ*) = 20°, with *dashed lines* for *SAZ* = 90° and *dot-dashed lines* for *SAZ* = 160°.

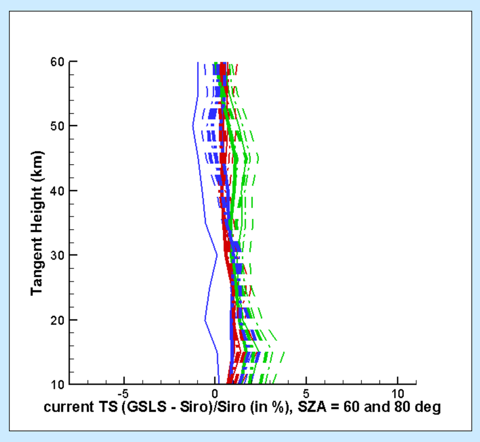
Note: The Siro τ method can be computed analytically, so its computational cost is modest.



Multiple MS Zeniths

The L04 GSLS model also computes the multiple-scattering (MS) source function for the single zenith (OT above) that intersects the tangent point for the line of sight (LOS) of interest. The current GSLS model can instead compute MS source functions at several zeniths (e.g., OA, OP, OT, OQ, OE above). This modification allows better representation of the MS source function, as shown below in improved total-scatter (TS = SS + MS) radiance agreement with Siro, at the cost of ≈ 8 times the run time (for unpolarized RT, at 17 MS zeniths).





TS Radiance Comparison

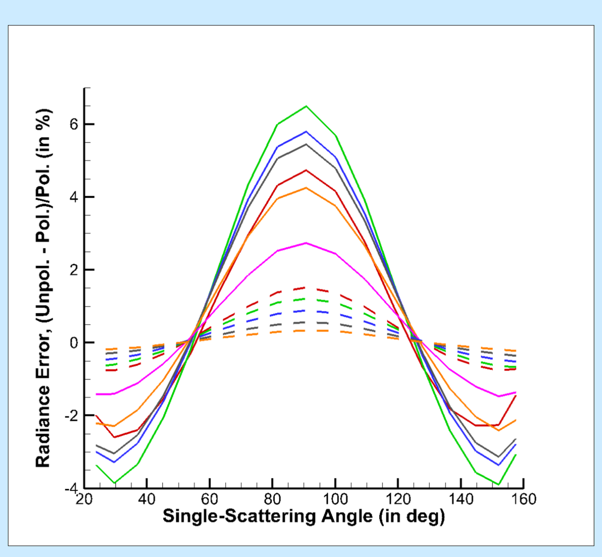
The figures above compare Siro TS radiances to L04 GSLS (left) and current GSLS (right) TS radiances for *SZA* = 60° (*thinner lines*) and 80° (*thicker lines*). The line styles and colors have the same meaning as in the previous SS comparisons. The Lambertian surface reflectivity *R* = 0.95, and the current GSLS model uses 17 MS zeniths along the LOS.

The improvement in TS radiance due to adding MS zeniths is slight when *SZA* ≈ 0° or *SAZ* ≈ 90°, because those conditions minimize the variation of the solar illumination along the LOS. The current GSLS model is not yet capable of accurate MS source function calculations when *SZA* > 90°. In the future, the multi-zenith MS GSLS model will be tested for twilight conditions, as well as other scenarios that the L04 GSLS model cannot simulate (e.g., surface or atmospheric variation along the LOS).

Finally, the current GSLS TS radiances uniformly exceed the Siro values by a small amount (1-2%) for the case shown. The observed over-estimate increases with increasing *R*, and requires further study. It may occur because RT models using flat (or pseudo-spherical, like GSLS) atmospheres for MS calculations over-estimate upwelling radiation[3].

Polarization Improvement

The ability to calculate polarized radiances was not retained as the L04 GSLS model was adapted for the OMPS LP retrieval algorithms[4]. The current GSLS restores this capability, verifying the polarized radiances by comparison to Fig. 3 of *reference 1* and the tabulated values of *reference 5*. Neglecting polarization produces little retrieval error because the OMPS LP retrieval algorithms use radiance ratios, but unpolarized radiances differ significantly from correct polarized radiances as shown below.



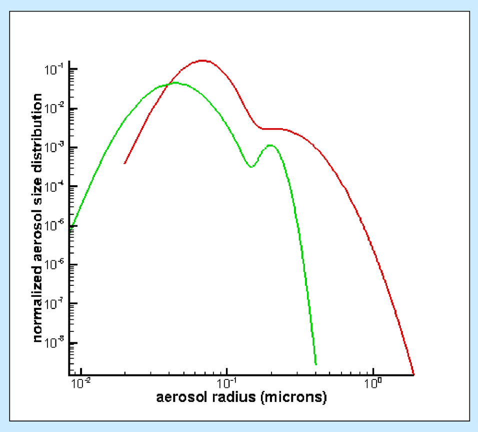
Polarization Discussion

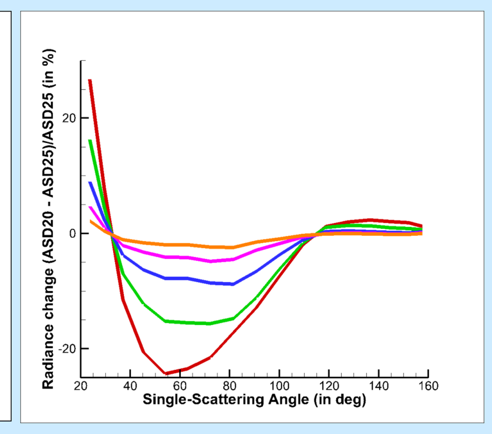
The figure in the previous column shows the unpolarized TS radiance error as a function of SS angle for the viewing geometry of a simulated OMPS LP orbit. The tangent height *h* = 40 km, *R* = 0, and the curves indicate the error associated with 325, 345, 385, 400, 449, 521 nm (solid lines) and 602, 676, 756, 869, 1020 nm (dashed lines). The overall behavior of these curves follows the expected pattern[6], with largest errors appearing at 345 nm, when:

- *Rayleigh* scattering dominates
- Just a few scattering events are likely for a typical photon (vertical optical depth ~ 1)
- Absorption is weak
- Surface reflection is small

Improved ASD Capability

Stratospheric aerosol measurement campaigns clearly demonstrate that the aerosol size distribution (ASD) varies significantly with altitude (typically with smaller particles at higher altitudes)[7]. The current GSLS model has been updated to allow the aerosol phase function to vary with altitude. As a rough indication of the significance of this variation, the TS 676 nm radiance change is shown below for a simulated OMPS LP orbit in which the aerosol phase function differs, but all other quantities (including aerosol extinction coefficient) are fixed.





ASD Discussion

The left panel above shows bi-modal log-normal ASDs based on data for 6 balloon flights over Laramie, Wyoming during 2012, at 20 km and 25 km[8]. The right panel shows how the TS radiance changes when each ASD is used (for the entire atmosphere), at *h* = 20, 25, 30, 35, 40 km. The magnitude of the radiance sensitivity to ASD (right panel) suggests that over-simplified portrayal of the stratospheric ASD (e.g., excluding the phase function variation with altitude) may be a significant source of aerosol extinction retrieval error.

OMPS Retrieval Simulation

An orbit of simulated OMPS radiances (including 17 cases, evenly spaced across the sunlit hemisphere) was generated to perform an initial assessment of the significance of the GSLS RT model changes for the ozone retrieval. To isolate the effect of the RT model changes, many simplifications are used relative to the normal OMPS LP retrieval:

- Noise-free simulated OMPS LP measurements with *R* = 0.3 across the entire orbit
- Aerosol and NO_2 profiles are known perfectly by the ozone retrieval algorithm
- Tangent height (*h*) registration and surface reflectivity retrievals occur as usual, prior to the ozone profile retrieval

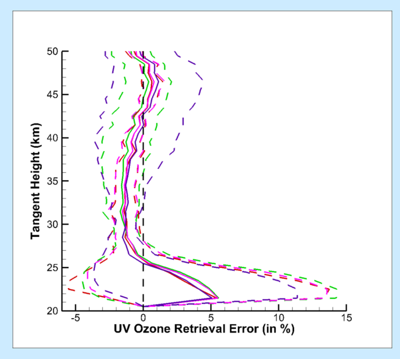
OMPS Retrieval Characteristics

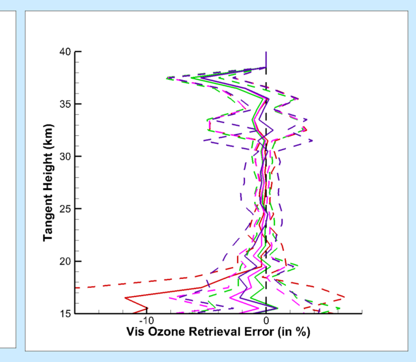
For the base case (pink lines), both the forward simulations and the retrieval algorithm use a RT model in which:

- Simulated radiances are scalar (unpolarized)
- A single zenith is used to calculate MS source functions
- The L04 GSLS method is used to calculate τ

The other cases differ from the base case by:

- Forward simulation RT model uses Siro method to calculate τ
- Vector (polarized) forward simulation radiances
- Forward simulation uses 17 MS zeniths

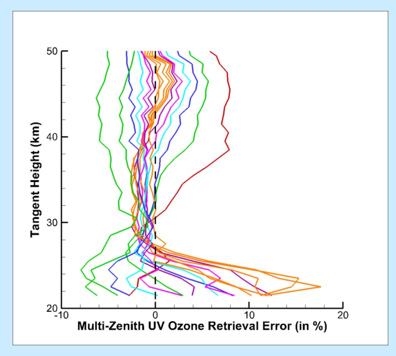


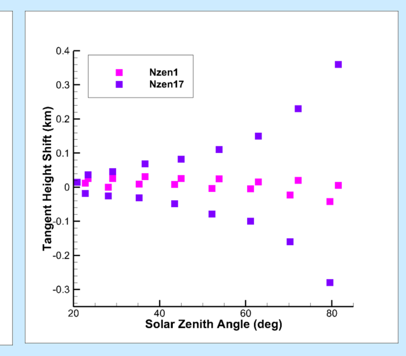


Ozone Retrieval Error

The figures above show the retrieval % error (Δx, solid line) ± the standard error in Δx (σ_x, dashed lines). The UV Δx (left panel) has a small (< 2%) bias in all cases, primarily due to ozone a-priori profile influence. The polarized and multi-zenith cases show higher σ_x values, driven primarily by *h* registration error in both cases (see below).

For the Vis retrieval (right panel above), the Siro τ case shows larger σ_x as well as significant Δx bias at the lowest *h* values, primarily due to tropical cases with very little ozone at h < 20 km. The multi-zenith case again shows larger σ_x throughout the retrieved altitude range.





Ozone Retrieval Discussion

The left figure above shows the 17 individual event UV retrieval errors in the multi-zenith case, which clearly increase with *SZA*: The line colors indicate cases with *SZA* > 80°, 70°, 60°, 50°, 40°, and 30°, respectively. The right figure shows how shifts in *h* (which should ≈ 0, as they do for the single-zenith base retrieval) grow as large as 400 m as *SZA* → 90° in the multi-zenith case, leading to ozone retrieval error.

Summary

Improvements in the current GSLS RT model significantly improve the calculated radiances relative to the L04 GSLS model, with SS radiance error now generally < 0.5% and TS radiance error at the 1-2% level. As shown in previous work, the OMPS LP ozone retrieval algorithm is resilient, tolerating numerous RT approximations without significantly changing the retrieved profiles. This work suggests that using the multi-zenith GSLS model would significantly improve the OMPS LP *h* registration for retrievals at large *SZA*, and should be considered.

Acknowledgements

This research was supported by NASA GSFC through SSAI Subcontract 21205-12-043. The authors thank NASA and NOAA for supporting limb scattering research, and particularly recognize Didier Rault for years of leadership developing the OMPS LP algorithms. Larry Thomason and Terry Deshler shared helpful insights into the stratospheric aerosol problem. The SSAI and NOAA OMPS teams supported this research and contributed many useful discussions, including Ghassan Taha, Larry Flynn, Zhong Chen, Philippe Xu, Tong Zhu, Nick Gorkavyi, Al Fleig, Jack Larsen, Mike Linda, and Leslie Moy. Several HU students contributed to the OMPS LP algorithms, including Daryl Ludy, Simone Hyater-Adams, Ricardo Uribe, Curtis Driver, Jonathan Geasey and Nicholas Carletta. We appreciate the OSIRIS, SCIAMACHY, SAGE II, SAGE III and U. of Wyoming measurement teams, for maintaining and sharing their high-quality data sets. Finally, we thank Alexei Rozanov and the U. of Bremen team for enabling remote participation in this workshop.

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