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A fast code for channel limb radiances with gas absorption and scattering in a spherical atmosphere

Janusz Eluszkiewicz [a], Gennady Uymin [a], David Flittner [b], Karen Cady-Pereira [a], Eli Mlawer [a,*], John Henderson [a], Jean-Luc Moncet [a], Thomas Nehrkorn [a], Michael Wolff [c]

[a] Atmospheric and Environmental Research, 131 Hartwell Ave., Lexington, MA 02421, USA
[b] NASA Langley Research Center, USA
[c] Space Science Institute, USA

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ABSTRACT

We present a radiative transfer code capable of accurately and rapidly computing channel limb radiances in the presence of gaseous absorption and scattering in a spherical atmosphere. The code has been prototyped for the Mars Climate Sounder measuring limb radiances in the thermal part of the spectrum (200–900 cm^{-1}) where absorption by carbon dioxide and water vapor and absorption and scattering by dust and water ice particles are important. The code relies on three main components: 1) The Gauss Seidel Spherical Radiative Transfer Model (GSSRTM) for scattering, 2) The Planetary Line-By-Line Radiative Transfer Model (P-LBLRTM) for gas opacity, and 3) The Optimal Spectral Sampling (OSS) for selecting a limited number of spectral points to simulate channel radiances and thus achieving a substantial increase in speed. The accuracy of the code has been evaluated against brute-force line-by-line calculations performed on the NASA Pleiades supercomputer, with satisfactory results. Additional improvements in both accuracy and speed are attainable through incremental changes to the basic approach presented in this paper, which would further support the use of this code for real-time retrievals and data assimilation. Both newly developed codes, GSSRTM/OSS for MCS and P-LBLRTM, are available for additional testing and user feedback.

1. Introduction

Measurements of the Martian atmosphere have experienced rapid growth during the past two decades. As on Earth, remote sensing from orbiting satellites offers the advantage of repeated global coverage. A host of instruments have been employed for this purpose, including cameras [the Mars Orbiter Camera (MOC) and the Mars Color Imager (MARCI)] and infrared sounders [the Thermal Emission Spectrometer (TES), the Mars Climate Sounder (MCS), and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)]. The MCS is a dedicated atmospheric instrument [22], while the other instruments have yielded a wealth of information about the atmosphere in addition to their primary surface-studies focus.

From the point of view of atmospheric studies, the dedicated limb-observing capability of the MCS, as well as the limb viewing "of opportunity" afforded by the TES, MOC, MARCI, and CRISM instruments offer some significant advantages compared with nadir observations. The geometry of limb measurements is illustrated in Fig. 1. Chief among the advantages are the improved vertical resolution (particularly relevant to studies of dynamic phenomena that are reflected in the thermal and aerosol structure) and the fact that observing against a cold space background offers the possibility of retrieving vertically resolved information about aerosols (including dust and H_2O and CO_2 ices) and minor gases (water vapor, carbon monoxide, etc.). In addition to retrievals, limb measurements are important for the application of data assimilation to the Martian atmosphere. Multiple years of infrared channel radiance observations collected by satellites orbiting Mars have been used to create "re-analyses" of the Mars atmosphere [e.g., [10]]. Such reanalyses are gridded representations of the Mars atmosphere produced every few hours by data assimilation systems that combine detailed general circulation models of the Mars atmosphere with data analysis techniques, such as the ensemble Kalman filter used in [10]. Either radiances or retrieved profiles of temperatures and constituents can be assimilated, but in both cases the quality of the resulting retrievals or reanalyses depends on the accuracy of the forward calculation of radiances from a specified atmospheric state.

The main limitation to attaining the full scientific potential of

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* Corresponding author.
E-mail address: mlawer@aer.com (E. Mlawer).

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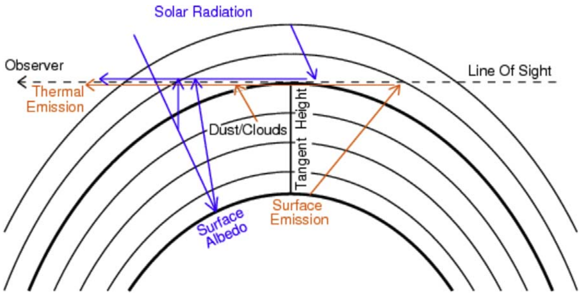

Fig. 1. The limb-viewing geometry. The radiances measured by the observer come from the Sun (e.g., cameras, CRISM) or thermal emission (e.g., MCS, TES). The planetary curvature has been exaggerated to illustrate the increased path length of the tangent atmospheric layer.

limb measurements has been the general lack of appropriate public-domain radiative transfer models. Such models must be capable of accurately modeling the impact of aerosol scattering and gaseous absorption in a spherical geometry in a computationally efficient manner suitable for retrieval and radiance assimilation work. The ubiquitous nature of aerosols in the Martian atmosphere enhances the importance of scattering for limb viewing geometry (versus that of nadir), e.g., a normal optical depth of 0.4 produces a line-of-sight optical depth of approximately 3 and 7 for tangent point altitudes 20 km and 10 km, respectively. (An illustration of a tangent height is provided in Fig. 1.) These numbers assume that the aerosols are uniformly mixed (with a scale height of 10 km). In fact, there is evidence that suggests that dust is actually more confined during lower opacity periods [e.g., [39]], increasing the slant optical depths even more for the lower tangent points.

Given the complexity of the limb scattering problem, past approaches have often neglected scattering [e.g., [18]] or treated it in a simplified manner, either by adapting a single-scatter approximation [19] or by using models developed for plane-parallel geometry [34]. Validation of these approaches has been limited to cases without gaseous absorption. The goal of this work is to provide an accurate forward calculation of radiances observed in limb geometry for Mars when both scattering and gaseous absorption are important so that such data may be optimally utilized for retrievals and data assimilation.

The work described here has two main components. First we introduce a set of rigorous reference calculations against which approximate methods to the limb absorption in scattering atmospheres can be validated. These calculations will be carried out by means of the spherical limb code of [14,15] for scattering (Section 2) and a planetary adaptation of the line-by-line (LBL) model LBLRTM [8] for gaseous absorption (Section 3). The second component and main objective of the paper is to describe a fast parameterization capable of accurately and efficiently calculating spectrally integrated limb radiances in the presence of gaseous absorption and scattering by aerosols. At the heart of this parameterization lies the Optimal Sampling Method (OSS) for gaseous absorption [25] that has been specifically designed to reproduce the accuracy of LBL calculations, but at a miniscule fraction of the computational cost. The OSS method treats gaseous absorption monochromatically, making it a natural choice for coupling to a scattering code. The OSS approach and an OSS-based parameterization for the MCS instrument are described in Section 4, which also presents the results of validation of this parameterization with respect to the reference calculations. A summary is provided in Section 5.

2. Limb scattering model

The multiple-scattering radiative transfer model (RTM) chosen for this project, the Gauss Seidel Spherical RTM (GSSRTM) [14,15], has been in use for more than 20 years. It is designed for scattering within a spherical planetary atmosphere and originated in one of the first RTMs used for scattering by aerosols [12,13]. Scattering by molecules, dust, and clouds is explicitly included. The spherical atmosphere version of the GSSRTM has two distinct versions, one able to compute polarized scattering [15] while the other neglects polarization during the scattering process [so-called scalar-approximation; [14]]. The model is monochromatic in nature and treats explicitly the geometry of a spherical-shell atmosphere. It has been used most extensively for solar scattering in the Earth's atmosphere at wavelengths ranging from the ultra-violet to the near infrared (i.e., non-thermal), including the analysis of space-based observations of light scattered from the limb of the Earth's atmosphere [23,29]. For the thermal infrared work described below, we employ the faster scalar mode with very little loss in accuracy (Rayleigh scattering opacity is negligible and aerosols are expected to be randomly oriented). This provided a significant reduction in run-time compared to the “full Stokes vector” version of GSSRTM. The model's assumption of spherical-shell symmetry means that the layers of the model atmosphere vary only in the radial direction (the input atmosphere is 1-dimensional). However, the radiance field is 3-dimensional with respect to position and 2-dimensional with respect to the look direction. The code has the capability to compute the first order (single) scattering independently of the total scattered radiance. As a by-product of work over the years dealing with terrestrial scattering in the UV and visible, various approximations to multiple scattering in a spherical atmosphere have been added as options to GSSRTM.

In an atmosphere with temperatures typical for Mars, scattered solar radiance is negligible at mid-IR wavelengths compared to thermal emission. However, the presence of non-molecular scatterers, i.e. dust and ice, necessitates that scattering of the emitted photons be considered. Furthermore, variations in dust and ice concentrations affect the radiance vertical profiles, including heights above where the majority of aerosol opacity resides.

Loughman et al. [21] carried out a model comparison study that included codes applicable to terrestrial limb viewing observations. A precursor to GSSRTM was included in the analysis and performed within 2–4% of the reference radiances for all cases except extreme viewing geometries (i.e., very large solar incidence angles) near the terminator. With the current focus of the thermal IR, this limitation is not an issue. Nevertheless, given the general differences in the typical photon paths for solar- and thermal-dominated source functions, additional reference calculations under typical Martian aerosol loading conditions have been done to provide increased confidence. Following [21], we generate the reference radiances using a 3D Monte Carlo algorithm developed by [36] from a well-validated astrophysical code. Previous Mars applications of this algorithm include simulations of Hubble Space Telescope and Pathfinder visible imaging data sets [36], the MGS MOC and TES visible limb observations [39], and TES IR spectral and limb profiling [6,7]. It was also used to provide benchmark models for a MRO CRISM limb retrieval algorithm [35].

Here we validate GSSRTM calculations using simulated Mars radiances for a range of atmospheric dust loading using identical surface and atmospheric conditions. We adopted the T1 case from [19] and specify the dust vertical distribution by a uniform mixing ratio, normalized to produce column-integrated optical depths of 0.2, 0.5, and 0.8 at the reference wavelength of 463 cm^{-1} (the center of the MCS A5 channel). The surface is described by an emissivity of 0.99, a Lambertian emission function, and a temperature of 214 K. The viewing geometry is defined by an observer