Spectral Resolution Effects on Solar Irradiance Calculations

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Abstract

For this study, we compared the spectral and integrated irradiance computed by high-resolution and moderate-resolution radiative transfer models (FASE and MODTRAN). It was found that the spectral resolution of a top of the atmosphere solar irradiance, coupled with the spectral resolution of the model used to compute the atmospheric transmittance, can influence the calculation of integrated solar irradiance. Further, differences between FASE and MODTRAN3.5 transmission calculations were identified, and the MODTRAN band model was upgraded, resulting in MODTRAN3.7.

Introduction

The accuracy of atmospheric radiative transfer calculations depends primarily on how well the model inputs capture the variability of the physical environment. This includes knowledge of the molecular concentrations, how these concentrations affect the optical properties (via absorption and scattering spectroscopy), and the radiative transfer calculation itself. In the visible and near-infrared parts of the spectrum, the end-to-end atmospheric calculations also require knowledge of the magnitude and structure of the solar spectrum. The intent of this work was to evaluate the impact of spectral resolution on the calculation of the integrated solar irradiance. This was accomplished by comparing the spectra computed with the MODTRAN and FASE radiative transfer models using both the 1 cm^{-1}(a) and 0.01 nm(b) (0.156^{1} cm at 12,500 cm^{-1}; 1.89 cm^{-1} at 43,478 cm^{-1}) solar spectra. The models and solar spectra are described below and in Berk et al. (1983). The results illustrate the need to perform high-resolution calculations to resolve the structure of the spectra (including both atmospheric and solar features) and to characterize specific spectral features. However, more computationally efficient calculations at lower spectral resolution are sufficient for evaluating a large number of spectra and for calculating the integrated irradiance.

Radiative Transfer Models

MODTRAN (Moderate/2 cm^{-1} Resolution Transmission/Radiance Model) (Berk et al. 1983) and its predecessor LOWTRAN (Low/20 cm^{-1} Spectral Resolution Transmission/Radiance Model) are radiative transfer band models developed by the Air Force to predict atmospheric transmittances, radiances, and vertical fluxes. The latest publicly released version of MODTRAN, MODTRAN3.5, expands flexibility of cloud and geometry inputs over earlier versions of the model. MODTRAN3.7, currently in beta-testing, will include the upgrade to the band model described below, in order to improve transmittance predictions primarily in the short-wave through visible spectral regions.

FASCODE for the Environment (FASE) was developed by combining features from the line-by-line radiative transfer

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(a) R. Kuruca, Harvard-Smithsonian, private communication, 1994.

(b) K. Chance, Harvard-Smithsonian, private communication, 1994.

codes of the Air Force Phillips Laboratory (FASCODE) (Anderson et al. 1994) and the U.S. Department of Energy (DOE) (LBLRTM) (Clough 1992). Both of these models were derived from FASCOD3, which was based on FASCOD1B, a rapid line-by-line radiance and transmittance code with four-function line decomposition, developed by Clough et al. (1981) and Clough and Kneizys (1979). The rationale for the development of FASE is to make available to the atmospheric spectroscopy community the results of on-going work sponsored by DOE, while incorporating the results of continuing research and development at the Air Force Phillips Laboratory. An initial version of FASE (Snell et al. 1995a) was available for limited release and testing in the summer of 1995; beta-version 2.0 was available in June 1996. The reader is referred to the paper by Snell et al. (1995b), which describes the on-going effort to fully merge the capabilities of FASCODE and LBLRTM and provides information about recent model validations against measurements.

Both MODTRAN and FASE use the HITRAN96 database for line parameters and share the common elements of path geometry, Rayleigh scattering, molecular continuum, aerosol absorption, and heavy-molecule cross-sections. Comparisons of a monochromatic FASE calculation degraded to the MODTRAN spectral resolution give very good agreement. This is particularly important to note in the context of studies which require many calculations at moderate spectral resolution, because FASE is much more computationally intensive than MODTRAN.

Solar Spectra

Characteristics of the solar spectra examined for this study are summarized in Table 1. The spectra have been individually validated as well as cross-validated. Close examination of the Chance spectrum showed that it contains residual atmospheric O$_2$ lines (Figure 1). As a first-order correction, these regions were replaced with the Kurucz spectrum. Water vapor lines are also apparent between 13,000 and 14,000 cm^{-1}, but are weak and have not been corrected for in this study. A more elaborate correction involves accurately determining the oxygen and water-vapor column amounts and analytically removing the atmospheric absorption features. This task awaits future funding. While both spectra contain Fraunhofer solar absorption lines, the high-resolution Chance spectrum reveals much more of the detail of these features (e.g., around 1 cm^{-1} in Figure 1). Both spectra, however, agree to within 1% for the integrated irradiance (1,787 W/cm^2, after the correction of the Chance spectrum), which indicates that the differences in Fraunhofer line shape is due to the spectral resolution and not to inherent discrepancies between the two spectra.

Table 1. Solar spectra characteristics.

"Kurucz"	• Based on the line-by-line calculations of R. Kurucz • Spectral Range: 50 to 50,000 cm^{-1} at 1 cm^{-1} resolution • Over the range from 50 to 10,000 cm^{-1}, the spectrum has been degraded to 1 cm^{-1} resolution from a higher resolution calculation
"Chance"	• Based on a compilation of atmosphere-corrected balloon (39.7 km) (Anderson and Hall 1983) and Kitt Peak measurements compiled by K. Chance • Spectral Range: 230 to 800 nm (12,500 to 43,478 cm^{-1}) • Measurements resampled to a common grid of 0.01 nm ($\geq$0.15 cm^{-1}); interpolated to a 0.1 cm^{-1} grid for use with FASE

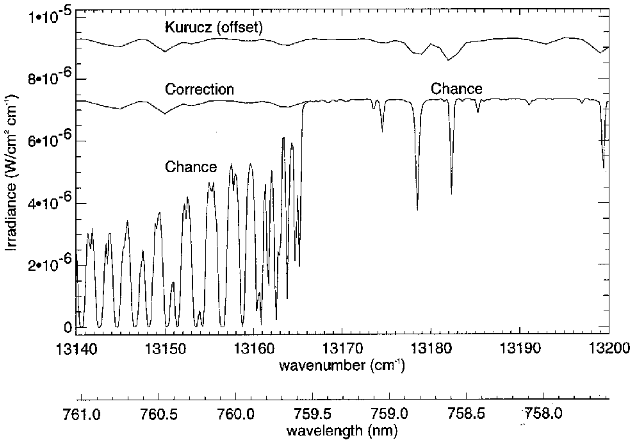

Figure 1. Comparison of the solar spectra used in this study. The residual oxygen lines in the Chance spectrum were corrected by replacing these regions with the Kurucz spectrum (<13,167 cm^{-1}). The Kurucz spectrum averages over the detailed Fraunhofer line shape (>13,167 cm^{-1}).

Transmitted Solar Irradiance

A series of tests was conducted whereby the codes computed the transmitted solar irradiance from the top-of-the-atmosphere (100 km) to the surface (0 km) at a solar zenith angle of 45 degrees. These calculations were initially done with FASE and MODTRAN3.5 for both solar spectra. Comparison of the FASE-calculated transmitted irradiance for the Kurucz and Chance spectra show that the use of the low-resolution Kurucz spectrum degrades the apparent spectral resolution of the FASE calculation. For example, Figure 2 illustrates the Kurucz and Chance spectra in the region of 15,250 to 15,300 cm^{-1}, the FASE calculations are shown in Figure 3. Note that the unresolved Fraunhofer features in the low-resolution solar spectrum, such as the line at 15,271 cm^{-1}, can obscure or distort the narrow molecular absorption lines in the calculation of the transmitted irradiance.

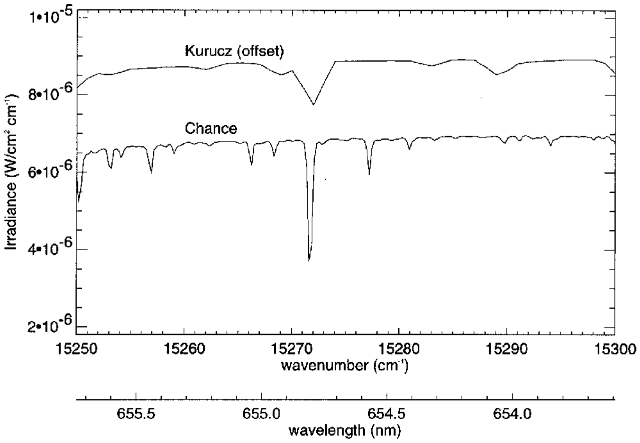

Figure 2. Comparison of the Kurucz and Chance spectra.

A comparison of FASE (with the Chance spectrum; monochromatic calculation degraded to 2 cm^{-1} resolution) and MODTRAN (2 cm^{-1} resolution; with the Kurucz spectrum) over the same spectral region (Figure 4a) shows very good agreement in the calculation of transmission. However, Figure 4b indicates that differences in the Kurucz and Chance spectral resolutions can influence the calculation of transmitted solar irradiance. This is particularly evident in regions where there is strong Fraunhofer absorption, such as that around 15,230 cm^{-1}.

In addition to spectral comparisons of FASE and MODTRAN, the attenuated irradiance was compared after integration over wide spectral intervals (Table 2). Despite noticeable differences in the spectral irradiance (e.g., Figure 4), there are only relatively small differences between the FASE and MODTRAN3.5 integrated solar irradiance. The largest differences occur in the 7000 cm^{-1} H2O band, but this region is nearly opaque and the contribution to the total irradiance is small. Note that the Chance spectrum covers the range from 12500 - 43478 cm^{-1}, with the exception of the O2 bands in that region. Thus the 15400 cm^{-1} H2O band was calculated using the Chance solar spectrum, while the other bands use the low-resolution Kurucz solar spectrum.

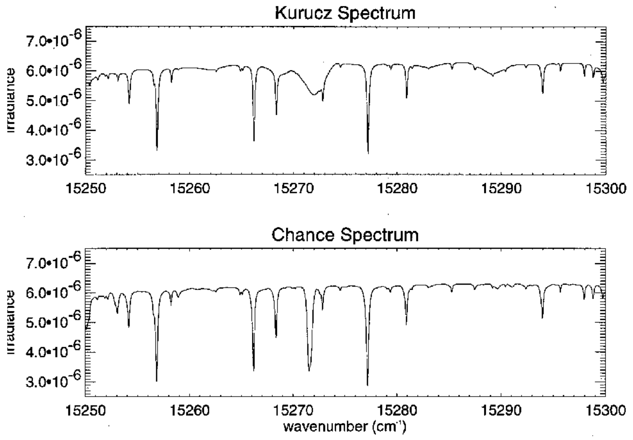

Figure 3. Comparison of the transmitted solar irradiance computed with FASE using the Kurucz and Chance solar spectra.

While the agreement between FASE and MODTRAN3.5 is very good, this study led to the recognition that parts of the

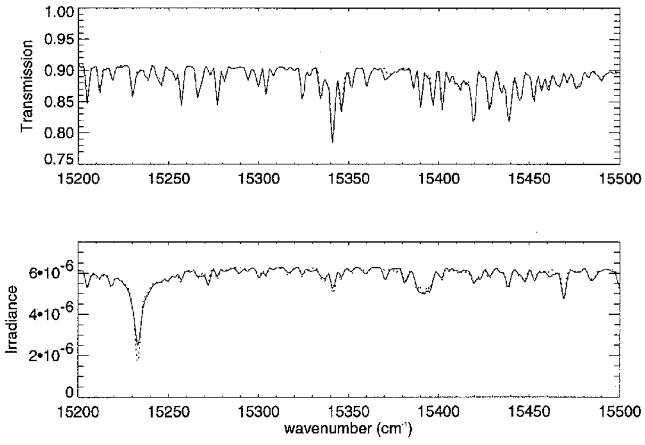

Figure 4. Comparison of MODTRAN (solid line) and FASE (dotted line) space-to-ground transmission and attenuated solar irradiance.

Table 2: Comparison of FASE and MODTRAN for irradiance integrated over discrete bands.

Spectral band	Spectral Region		Integrated FASE	MODTRAN 3.5	MODTRAN 3.7	FASE/MODTRAN
	cm^{-1}	nm		W/cm^{-2}		old ratio : new ratio
CO2	2000 - 3000	5000.00 - 3333.33	7.992E-04	7.906E-04	7.946E-04	1.011 : 1.006
H2O	5000 - 5600	2000.00 - 1785.71	4.091E-04	3.953E-04	4.069E-04	1.035 : 1.005
H2O	7000 - 7390	1428.57 - 1353.18	3.497E-05	3.157E-05	3.492E-05	1.108 : 1.001
H2O	8400 - 9400	1190.48 - 1063.83	4.940E-03	4.876E-03	4.908E-03	1.013 : 1.006
H2O	10580 - 10695	945.18 - 935.02	3.573E-04	3.445E-04	3.558E-04	1.037 : 1.004
H2O	11500 - 12500	869.57 - 800.00	6.715E-03	6.718E-03	6.720E-03	0.999 : 0.999
O2	12800 - 13170	781.25 - 759.30	2.067E-03	2.040E-03	2.058E-03	1.013 : 1.004
O2	14310 - 14560	698.81 - 686.81	1.450E-03	1.447E-03	1.448E-03	1.002 : 1.001
H2O	15000 - 15800	666.67 - 632.91	4.789E-03	4.786E-03	4.786E-03	1.001 : 1.001
O2	15710 - 15390	636.54 - 627.75	1.275E-03	1.274E-03	1.274E-03	1.001 : 1.001

MODTRAN band model required reformulation (Berk et al. 1997). MODTRAN3.5 models the relatively smooth absorption from all lines centered more than 0.2 cm^{-1} (but within 25 cm^{-1}) from a particular 1 cm^{-1} spectral bin using a single temperature-dependent 1 cm^{-1} line tail absorption coefficient. However, when molecular bands consist of strong, sparsely spaced lines (relative to the 1 cm^{-1} bins employed by MODTRAN), then adjacent bins, with and without lines, can be impacted by how these line tails are modeled. For instance, in the oxygen A-band these line tails can fall off significantly within a single 1 cm^{-1} bin. Band model parameters for higher spectral resolution (0.25 cm^{-1}) line tails have been generated and integrated into MODTRAN (as MODTRAN3.7) to better capture the variation of absorption across the individual 1 cm^{-1} spectral bins. The impact of the new formulation is small when many lines overlap within the 1 cm^{-1} bins, as in the infrared, generally overwhelming the discrete contributions of the tails. Isolated bands, e.g., the O2 A-band and near-IR H2O bands, are most impacted by this more physical description. The MODTRAN3.7 integrated solar irradiances are reported in Table 4. Differences between the FASE line-by-line calculation and MODTRAN3.7 do not exceed 0.6%, while MODTRAN3.5 predicts too little radiation by as much as 11%.

Conclusions

This study has shown that while the Kurucz and Chance solar spectra agree in integrated intensity, the higher resolution Chance spectrum reveals more information about the Fraunhofer structure. However, future work is required to adequately correct for the oxygen and water features found in the Chance spectrum. FASE and MODTRAN exhibit very good spectral agreement for atmospheric transmission and transmitted solar irradiance. However, in regions of Fraunhofer lines, some of the structure is captured by the degraded FASE calculation and not by MODTRAN. The comparison and cross-validation of FASE and MODTRAN3.5 revealed some differences that were subsequently corrected by the MODTRAN3.7 band model. In general, the spectral resolution of the calculation should be no less than the resolution of the solar spectrum used for the top-of-the-atmosphere irradiance. Thus, for calculations of the integrated solar irradiance, MODTRAN is a much faster alternative to FASE.

Acknowledgments

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