High-Resolution Model/Measurement Validations of Solar Direct-Beam Flux

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Introduction

A balance between thermal and solar radiation at the top of the atmosphere is necessary for the stability of the earth's climate. To evaluate the behavior of the climate system resulting from a radiative perturbation of this balance, as in a "global warming" scenario, accurate knowledge is needed of the radiative properties of the atmosphere both in the thermal- and solar-dominated spectral regions. A closure experiment, termed a Quality Measurement Experiment (QME), has been instrumental in determining the sources of greatest error in the infrared part of the spectrum (Brown et al. 1998). This approach has been extremely successful as implemented within the Atmospheric Radiation Measurement (ARM) Program, based primarily on comparisons between the measurements of the Atmospheric Emitted Radiance Interferometer (AERI) (Revercomb et al. 1994) and the calculations of the Line-by-Line Radiative Transfer Model (LBLRTM) (Clough et al. 1992; Clough and Iacono 1995). The current agreement in the longwave between model and measurement is ~2 Wm^{-2} for clear-sky conditions for which the atmospheric profile is accurately known (Brown et al. 1998). This success has led to the development of an accurate longwave rapid radiative transfer model (Mlawer et al. 1997), which has been incorporated into general circulation models (GCMs) (Iacono et al. 1999).

The state of knowledge of radiative transfer in the solar-dominated spectral region is not as advanced. Large residuals have been reported in recent comparisons of measurements and related model calculations of both clear-sky diffuse flux (Kato et al. 1997; Halthore et al. 1998) and total shortwave flux absorbed in clouds (Cess et al. 1995; Ramanathan et al. 1995; Pilewskie and Valero 1995). This has led to some speculation as to possible missing physics in the models, including an unknown gaseous absorber in the visible (Kato et al. 1997; Halthore et al. 1998), additional shortwave absorption by water vapor (Arking 1996, 1999), absorption by water vapor dimers and multimers (Chylek and Geldart 1997), and aerosols with unexpectedly low single-scattering albedos (Harrison et al. 1999; Mlawer et al. 1999a). In these studies, reporting "anomalous absorption," the ability to deduce the physical source of model-measurement residuals, has been limited due to the use of broadband, rather than spectral, observations and calculations. The uncertainty in the calibration of instruments that measure radiation at brightness temperatures in excess of 1000 K further limits accurate analyses (Kiedron et al. 1999; Michalsky et al. 1998; Dutton et al. 1999).

This report discusses the results of the first stage of a shortwave QME research effort to improve our understanding of shortwave radiative transfer using spectral validations of model calculations with observations. This first stage focuses on the direct solar beam in clear conditions. Similar to the successful longwave model-measurement intercomparison, the initial clear-sky emphasis is driven by the importance of gaining accurate knowledge of gaseous and aerosol radiative effects for all atmospheric conditions. The ability to accurately compute the attenuation of the direct solar beam is necessary to obtain a clear understanding of the diffuse flux, which arises out of direct beam extinction. In fact, the direct beam results presented in this work rule out certain suggested explanations for the discrepancy indicated by recent broadband comparisons between diffuse flux calculations and measurements. The shortwave QME for the clear sky analyzes three critical components: 1) the ability to accurately measure downwelling radiance, 2) the capability to model both terrestrial extinction and extraterrestrial radiance, and 3) the ability to accurately characterize the atmospheric state in the radiating column. The initial focus of this QME is upon the spectral regions measured by the University of Denver Absolute Solar Transmittance Interferometer (ASTI) (Murcray et al. 1996) and the State University of New York at Albany Rotating Shadowband Spectroradiometer (RSS) (Harrison et al. 1998), which together cover the spectral range 2000 cm^{-1} to 28600 cm^{-1}.

Line-by-Line Model

The LBLRTM used in this intercomparison is based on the model Fast Atmospheric Signature Code (FASCODE) (Clough et al. 1981). For the computations performed as part of this study, the High-Resolution Transmission (HITRAN) 96 data base (Rothman et al. 1998) with supplemental line parameter information of Toth et al. (1998) was used. At all pressures, LBLRTM uses the Voigt line shape with a line cutoff of 25 cm^{-1} from the line center. Other model features important in the calculation of optical depths include the treatment of line coupling to second order and the utilization of the Total Internal Partition Sums (TIPS) program for the temperature dependence of the line intensities. Also used by LBLRTM for these calculations was the continuum model CKD_2.3, which includes both self-broadened and foreign-broadened water vapor continuum components (Clough et al. 1989; Mlawer et al. 1999b). In the spectral region pertinent to this study, CKD_2.3 also includes continua from carbon dioxide, ozone (Chappuis and Hartley-Huggins bands), collision induced oxygen and nitrogen, as well as an implementation of Rayleigh extinction.

Kurucz Solar Source Function

A critical element of the radiative transfer in the shortwave is our knowledge of the solar source function (SSF). Under the current effort, a critical evaluation of the SSF is being undertaken. The SSF of Kurucz et al. (1992) is employed as a reference for interpreting differences between the line-by-line model calculations and the measurements in the context of potential error in the SSF itself. Three versions of the Kurucz SSF have been made available to the ARM community: 1) monochromatic resolution, 50 cm^{-1} to 50000 cm^{-1}, no chromosphere, full solar disk; 2) monochromatic resolution, 1000 cm^{-1} to 10000 cm^{-1}, no chromosphere, center of the solar disk for applications to the ASTI (0.4 radius of solar disk), and 3) spectral irradiance binned to 1 cm^{-1}, 50 cm^{-1} to 50000 cm^{-1}, no chromopshere, full solar disk. The monochromatic Kurucz solar source function for the full disk in the spectral range 0 cm^{-1} to 40000 cm^{-1} is shown in Figure 1.

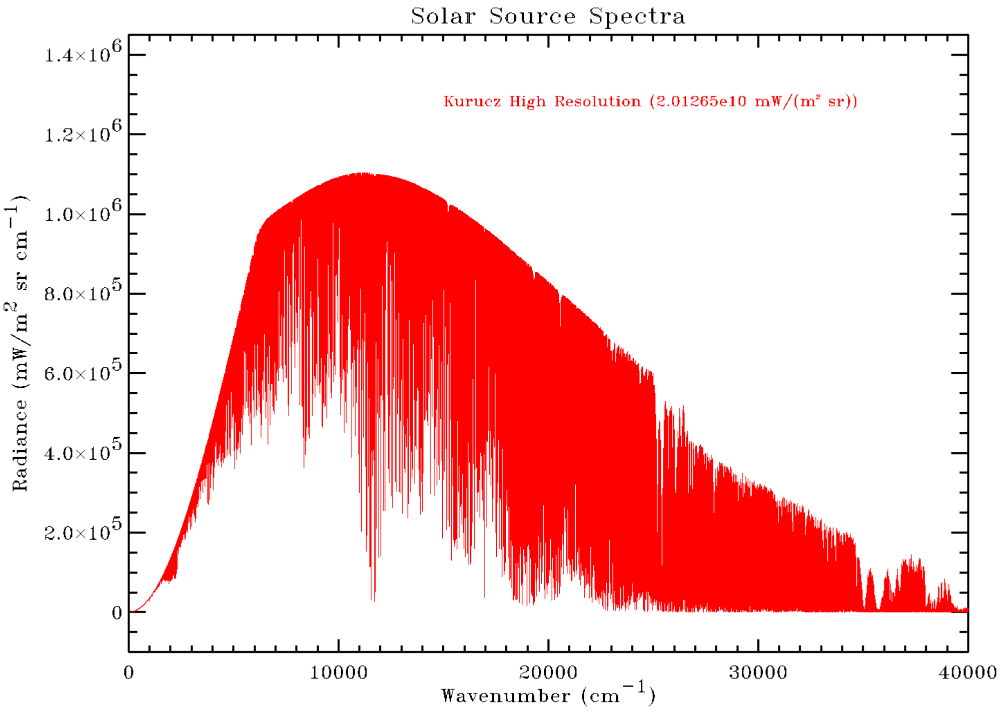


Figure 1. Kurucz monochromatic solar source function 0 cm^{-1} to 40000 cm^{-1}.

Specification of the Atmospheric State

Input profiles of atmospheric temperature and most trace gases are similar to those of the AERI/LBLRTM QME. Water vapor profiles are obtained by scaling the radiosonde profiles to be consistent in precipitable water column amount with the ARM Microwave Radiometer (MWR) measurement at 23.8 GHz. This method is identical to that used in the longwave AERI/LBLRTM QME. Climatological ozone profiles are scaled to agree with a spatially and temporally coincident TOMS-derived O_3 column value. Aerosol information is obtained as a product of the QME.

Measurements

The Absolute Solar Transmittance Interferometer

The high resolution content of the ASTI spectra provides an excellent dataset for identifying molecular absorption issues, assessing the ability to accurately measure radiation in the solar spectral regime, and evaluating the solar source function. The ASTI instrument is comprised of three filters over the spectral range 2000 cm^{-1} to 10000 cm^{-1} and has a resolution of 0.6 cm^{-1} half width at half maximum (HWHM). It measures the downwelling radiance in the direct solar beam, with a field of view (FOV) covering the central 16% of the solar disk (0.4 times the disk radius), and is collocated with the AERI instrument at the Southern Great Plains (SGP) central facility (CF). It uses a 2800-K tungsten lamp for calibration.

The Rotating Shadowband Spectroradiometer

The RSS instrument measures both total and diffuse irradiance at the surface, and thus the direct beam component can be obtained by subtracting the diffuse observation from the total measurement. The instrument for this study uses 512 channels over the spectral range 9300 cm^{-1} to 28600 cm^{-1} with an average width of 78 cm^{-1}. The spectral resolution has subsequently been increased to 1024 channels. While the resolution is not sufficient to study vibration-rotation lines, specific molecular bands can be accessed to suggest line parameter improvements. A Licor lamp is used for calibration.

Quality Measurement Experiment Results

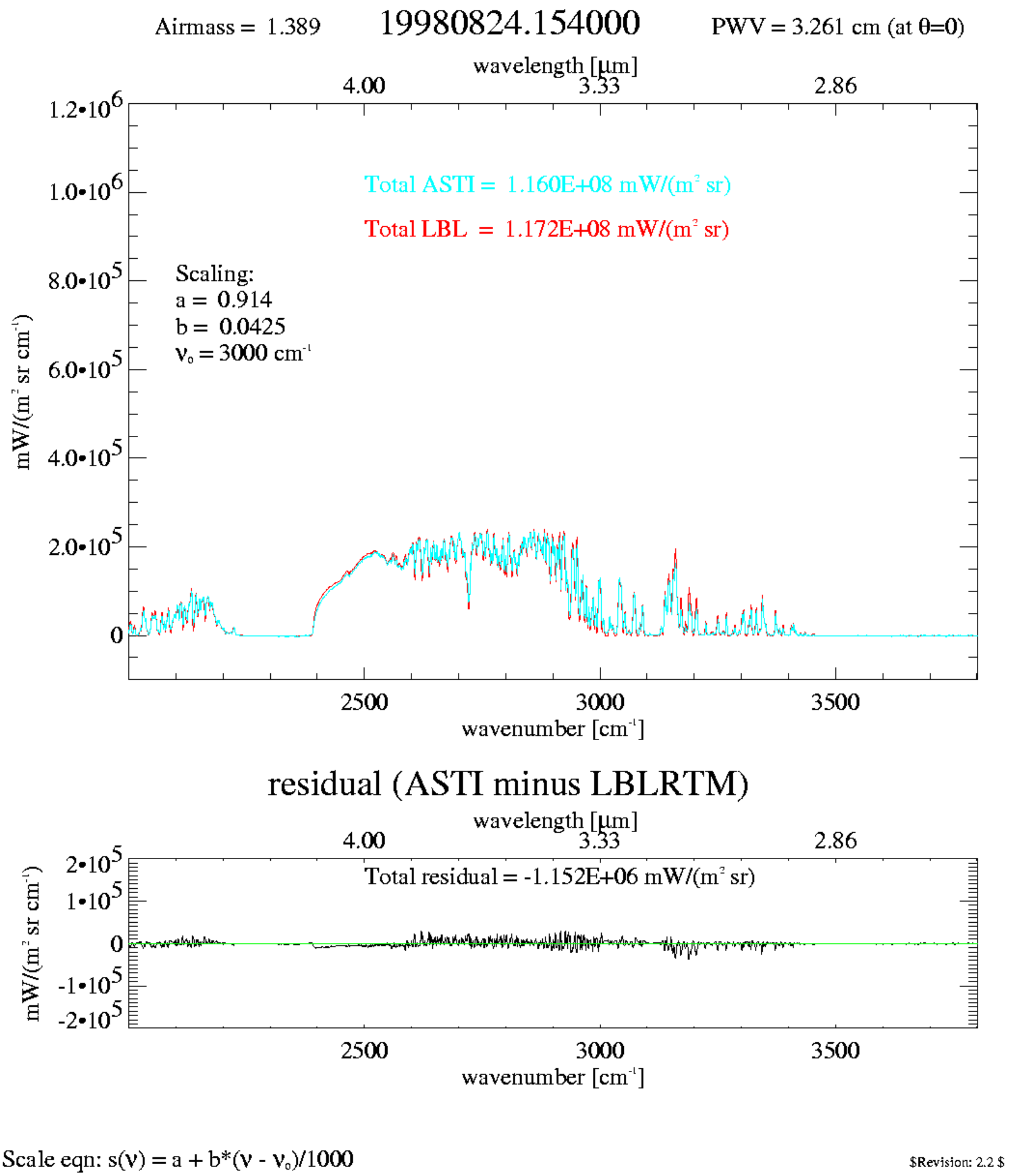
ASTI/LBLRTM QME

An ASTI/LBLRTM QME has been initiated over the past 1.5 years on an intensive operational period (IOP) basis and has provided significant results in terms of establishing our capability to model the solar spectral regime from 2000 cm^{-1} to 10000 cm^{-1} under clear-sky conditions. Based upon more than 50 clear-sky validations in this spectral regime, it has been established that there are no errors of significance in the modeling the irradiance at the surface for the direct beam under clear-sky conditions. In particular, it has been demonstrated there are no errors of significance to the modeling of the irradiance associated with the HITRAN 96 spectral line parameters or to the CKD water vapor continuum model. An example of an ASTI measurement and the spectral residual are provided in Figure 2. As a direct consequence of this ASTI/LBLRTM QME, two collision induced oxygen bands have been modeled and are now included in the CKD continuum model (Mlawer et al. 1998).

A constraint of this current QME is the limited data set from the ASTI, since it is being run on an IOP basis and is an instrument under continuing development. The situation with the ASTI is analogous to that of the University of Wisconsin Atmospheric Emitted Radiance Interferometer (AERI) circa 1990. Nevertheless, results from this QME have resolved speculation regarding the adequacy of the line parameters and the CKD continuum model for the spectral regime over which the instrument operates. An estimate of aerosol extinction can be made based upon the ratio of the LBLRTM calculation and the ASTI observation. Figure 3 compares the ASTI-derived estimate of aerosol optical depth (AOD) for 08/24/98 with that of the Multi-Filter Rotating Shadowband Radiometer (MFRSR) (Harrison et al. 1994) and the Angstrom fit using the MFRSR AODs to extrapolate down to the spectral regime of the ASTI.

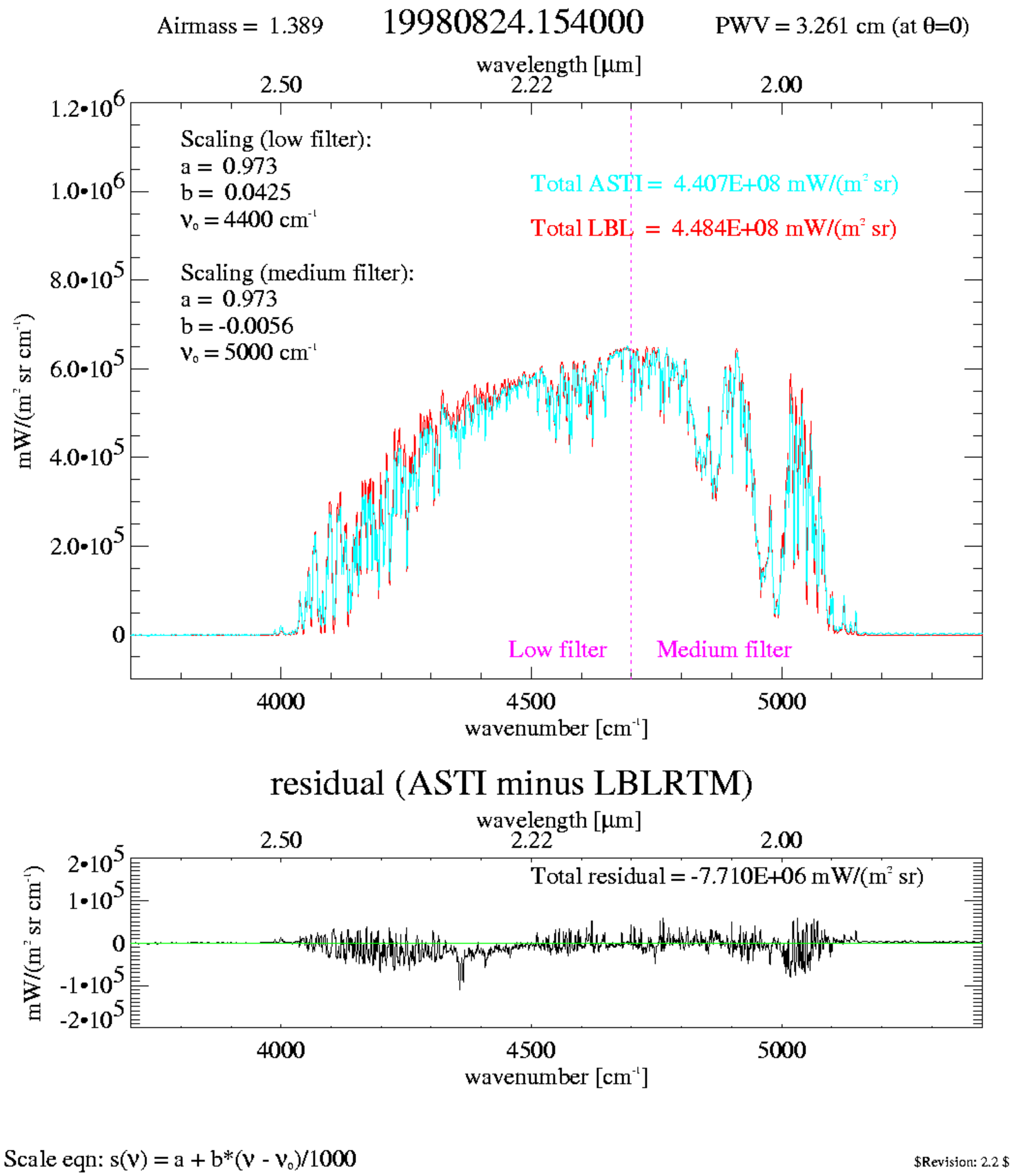
RSS/LBLRTM QME

Recently, an RSS/LBLRTM QME was initiated for the direct beam cases. Figure 4 shows a sample RSS observation, LBLRTM calculation, and the residuals for a case from October 1997. There is good overall agreement, to within approximately ~7 W/m^2 of the ~630 W/m^2 that reaches the surface. Some spectral issues remain, particularly in the water vapor and, to a lesser extent, oxygen bands from 10000 cm^{-1} to 14000 cm^{-1}. The model underestimates the absorption through these regions when compared to the measured value. Also, there appears to be a spectral shift in the RSS for the ν_2 oxygen A band region. While the sources of these errors are under investigation, it has been determined that there is no strong correlation between the integrated residuals and the path H_2O amounts.

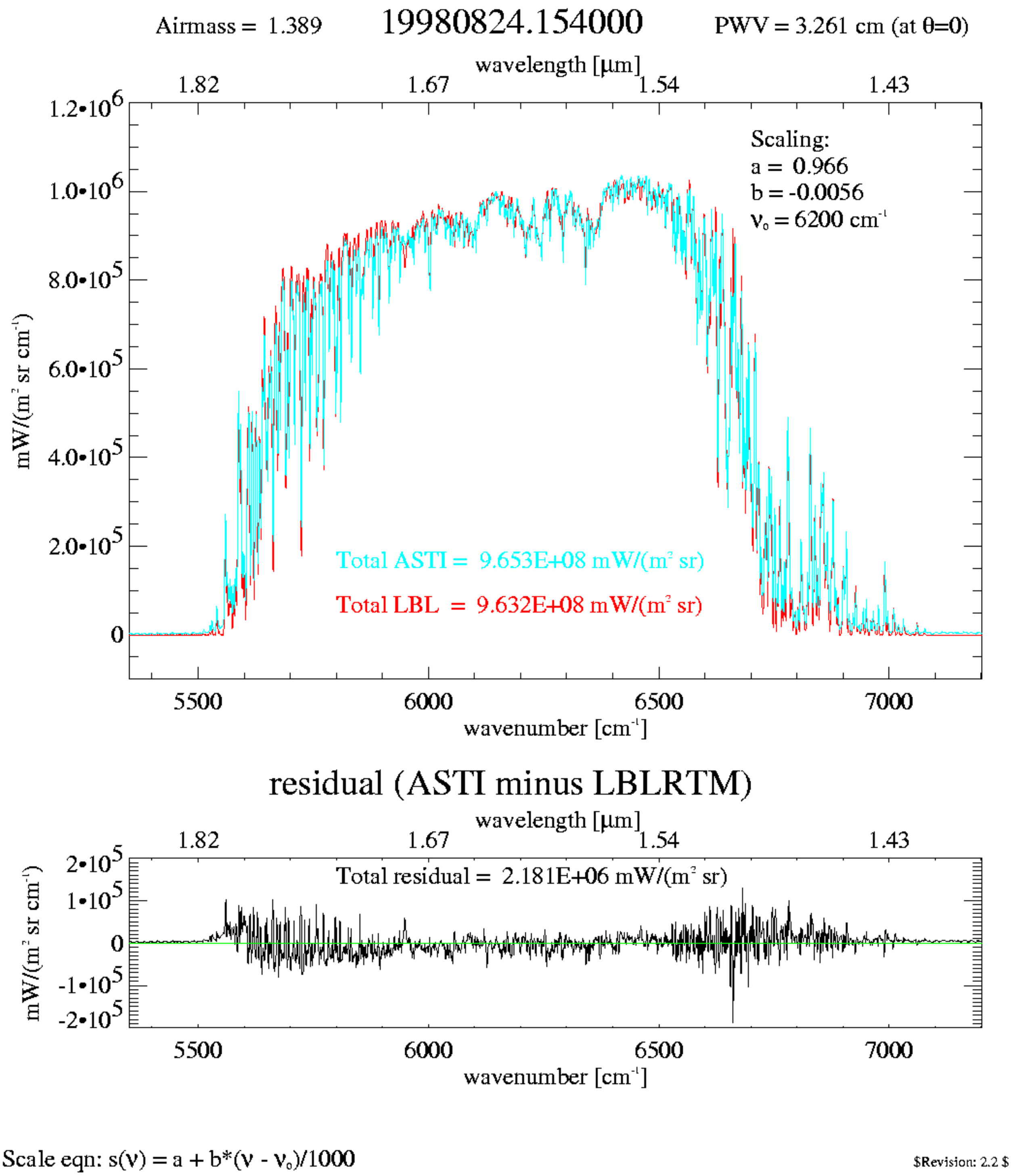


(a)

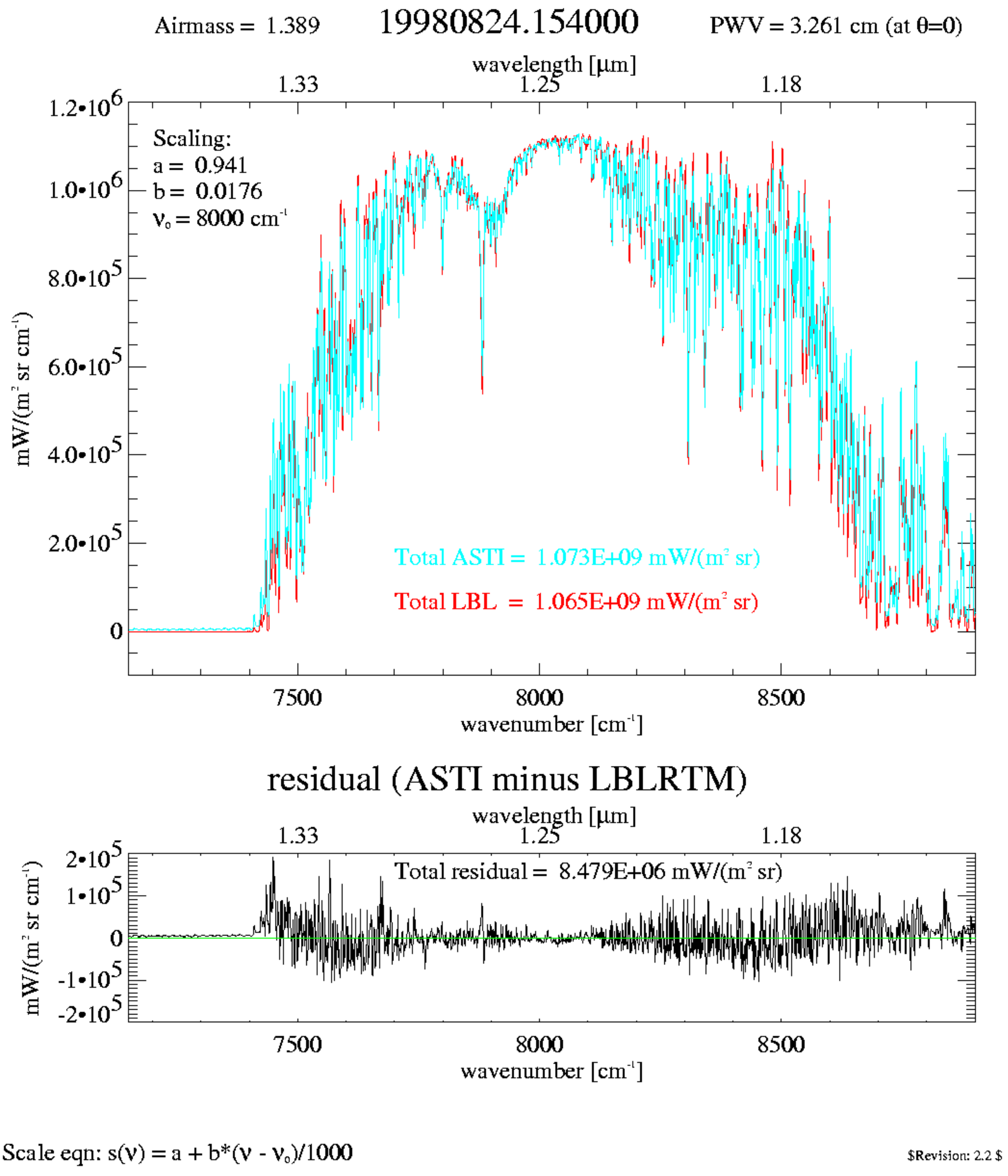
Figure 2. ASTI-measured (blue) overplotted LBLRTM calculated (red) surface radiance (top) and measured—calculated spectral residuals (bottom) for QME channel 1 (a), channel 2 (b), channel 3 (c), channel 4 (d), and channel 5 (e) for the 1540 Z case on August 24, 1998.


Airmass = 1.389
19980824.154000
PWV = 3.261 cm (at θ=0)
wavelength [μm]
2.50
2.22
2.00
1.2•10^6
1.0•10^6
8.0•10^5
6.0•10^5
4.0•10^5
2.0•10^5
0
mW/(m² sr cm⁻¹)
Scaling (low filter):
a = 0.973
b = 0.0425
ν₀ = 4400 cm⁻¹
Scaling (medium filter):
a = 0.973
b = -0.0056
ν₀ = 5000 cm⁻¹
Total ASTI = 4.407E+08 mW/(m² sr)
Total LBL = 4.484E+08 mW/(m² sr)
Low filter
Medium filter
4000
4500
5000
wavenumber [cm⁻¹]
residual (ASTI minus LBLRTM)
wavelength [μm]
2.50
2.22
2.00
2•10^5
1•10^5
0
-1•10^5
-2•10^5
mW/(m² sr cm⁻¹)
Total residual = -7.710E+06 mW/(m² sr)
4000
4500
5000
wavenumber [cm⁻¹]
Scale eqn: s(ν) = a + b*(ν - ν₀)/1000
$Revision: 2.2 $

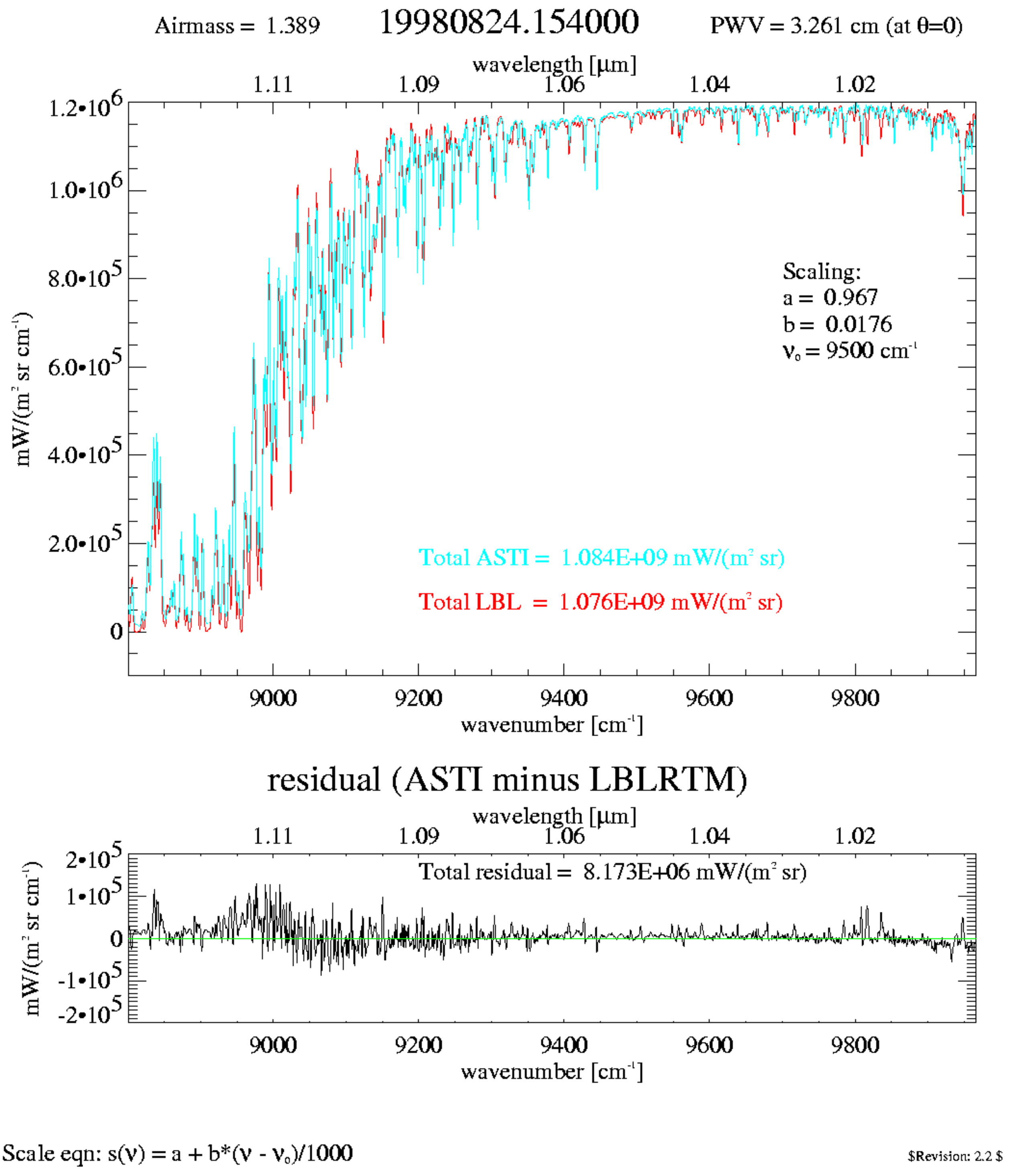
(b)


Airmass = 1.389
19980824.154000
PWV = 3.261 cm (at θ=0)
wavelength [μm]
1.82
1.67
1.54
1.43
1.2•10^6
1.0•10^6
8.0•10^5
6.0•10^5
4.0•10^5
2.0•10^5
0
mW/(m² sr cm⁻¹)
Scaling:
a = 0.966
b = -0.0056
ν₀ = 6200 cm⁻¹
Total ASTI = 9.653E+08 mW/(m² sr)
Total LBL = 9.632E+08 mW/(m² sr)
5500
6000
6500
7000
wavenumber [cm⁻¹]
residual (ASTI minus LBLRTM)
wavelength [μm]
1.82
1.67
1.54
1.43
Total residual = 2.181E+06 mW/(m² sr)
2•10^5
1•10^5
0
-1•10^5
-2•10^5
mW/(m² sr cm⁻¹)
5500
6000
6500
7000
wavenumber [cm⁻¹]
Scale eqn: s(ν) = a + b*(ν - ν₀)/1000
$Revision: 2.2 $

(c)


Airmass = 1.389
19980824.154000
PWV = 3.261 cm (at θ=0)
wavelength [μm]
1.33
1.25
1.18
1.2•10^6
1.0•10^6
8.0•10^5
6.0•10^5
4.0•10^5
2.0•10^5
0
mW/(m² sr cm⁻¹)
Scaling:
a = 0.941
b = 0.0176
ν₀ = 8000 cm⁻¹
Total ASTI = 1.073E+09 mW/(m² sr)
Total LBL = 1.065E+09 mW/(m² sr)
7500
8000
8500
wavenumber [cm⁻¹]
residual (ASTI minus LBLRTM)
wavelength [μm]
1.33
1.25
1.18
2•10^5
1•10^5
0
-1•10^5
-2•10^5
mW/(m² sr cm⁻¹)
Total residual = 8.479E+06 mW/(m² sr)
7500
8000
8500
wavenumber [cm⁻¹]
Scale eqn: s(ν) = a + b*(ν - ν₀)/1000
$Revision: 2.2 $

(d)


Airmass = 1.389
19980824.154000
PWV = 3.261 cm (at θ=0)
wavelength [µm]
1.11
1.09
1.06
1.04
1.02
1.2•10^6
1.0•10^6
8.0•10^5
6.0•10^5
4.0•10^5
2.0•10^5
0
mW/(m² sr cm⁻¹)
Scaling:
a = 0.967
b = 0.0176
ν₀ = 9500 cm⁻¹
Total ASTI = 1.084E+09 mW/(m² sr)
Total LBL = 1.076E+09 mW/(m² sr)
9000
9200
9400
9600
9800
wavenumber [cm⁻¹]
residual (ASTI minus LBLRTM)
wavelength [µm]
1.11
1.09
1.06
1.04
1.02
2•10^5
1•10^5
0
-1•10^5
-2•10^5
mW/(m² sr cm⁻¹)
Total residual = 8.173E+06 mW/(m² sr)
9000
9200
9400
9600
9800
wavenumber [cm⁻¹]
Scale eqn: s(ν) = a + b*(ν - ν₀)/1000
$Revision: 2.2 $

(e)

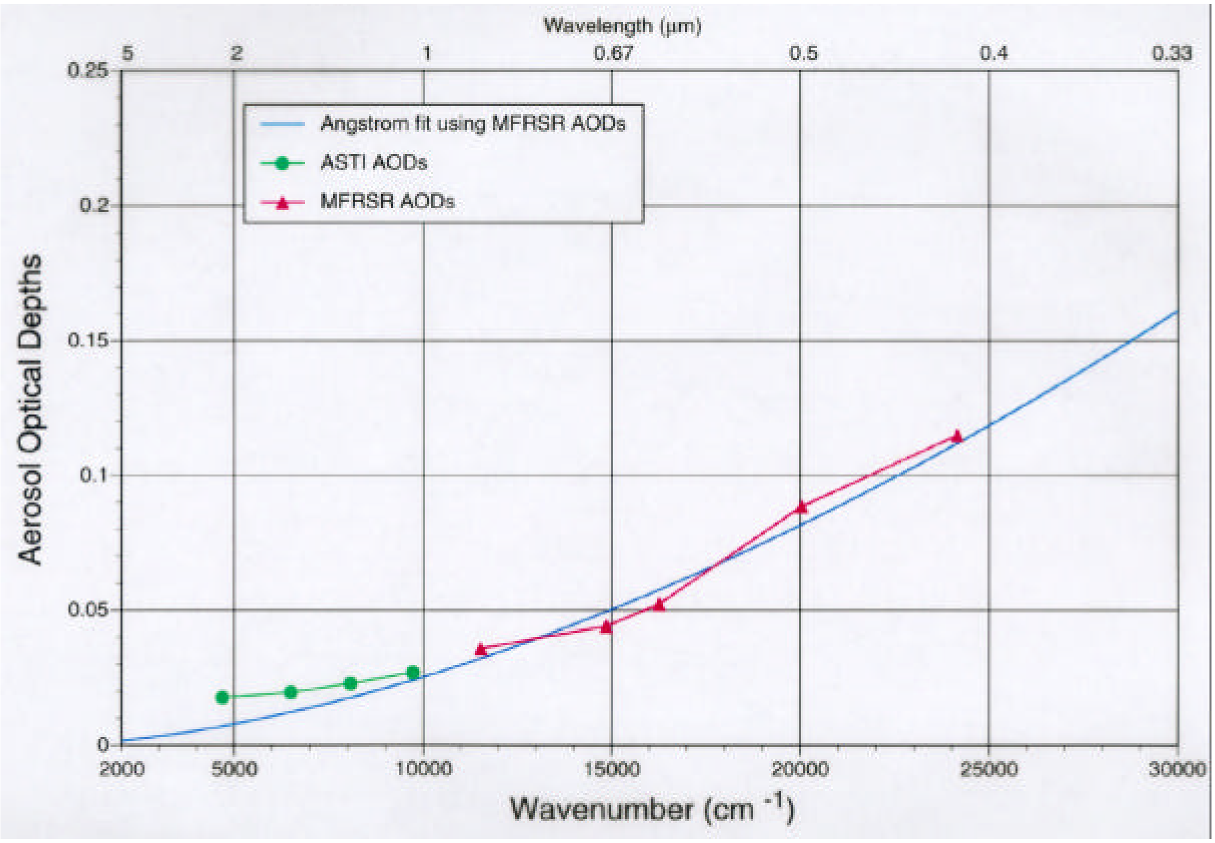


Figure 3. ASTI/LBLRTM QME-derived Aerosol Optical Depths (green) compared with MFRSR-derived AODs (red) for August 24, 1998. The blue curve describes the Angstrom fit to the MFRSR AODs applied to the 2000 cm^{-1} to 30000 cm^{-1} region.

Using the measurement/model comparison, values of two variables a and b can be derived for an Angstrom relation $a\lambda^b$ to describe the aerosol extinction associated with a given case. In Figure 5, The RSS-derived AODs for clear-sky cases over the time period September 27 to October 5, 1997, are compared to MFRSR-derived optical depths over the same time period. The optical depth values at 550 nm and 700 nm are given as reference values, and demonstrate that the RSS-derived AODs are consistent with the MFRSR product.

Conclusions

As a result of QME studies from the microwave to the shortwave, one can conclude that there is no evidence of significant unexplained absorption in the direct beam in the spectral regime 550 cm^{-1} to 28,535 cm^{-1}. Furthermore, the QME structure has provided a good mechanism for estimating spectral AODs that are in agreement with independent radiometrically-derived measurements of AODs. The ASTI/LBLRTM QME has led to a formulation of O_2 continuum absorption bands centered at 7874 cm^{-1} and 9434 cm^{-1}. While there is still uncertainty in the Kurucz SSF, particularly with respect to individual lines, both the ASTI/LBLRTM and the RSS/LBLRTM have helped to validate the general behavior of the extraterrestrial spectrum.

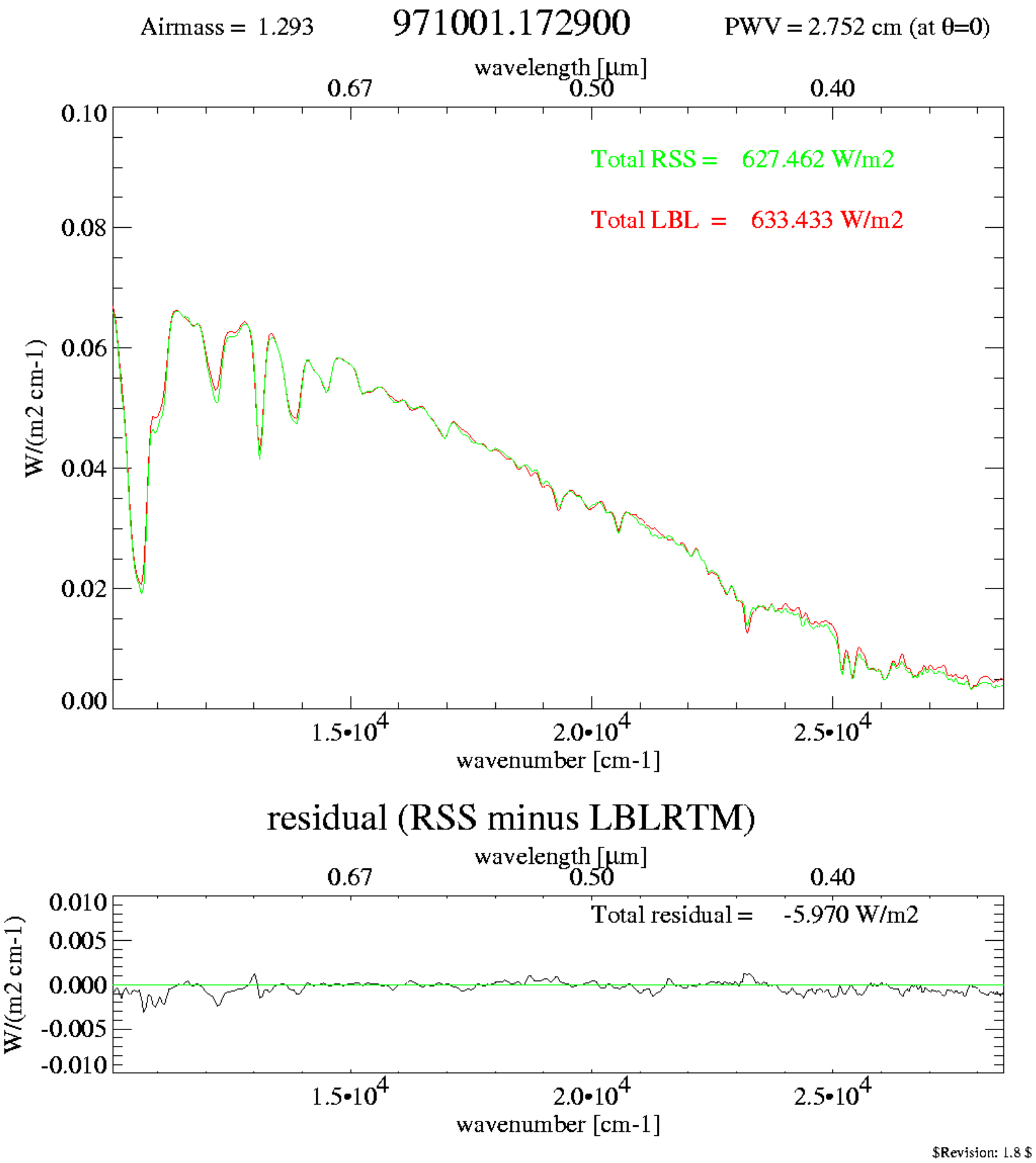


Figure 4. Sample RSS/LBLRTM validation for a clear-sky case in the direct beam from 1729 Z October 1, 1997. (top) The LBLRTM calculation (red), overplotted by the RSS measurement (green), includes an estimate of aerosol extinction in the calculation. (bottom) The RSS/LBLRTM spectral residuals are to within 6 W/m^2 of the 627 W/m^2 observed in the direct beam at the surface.

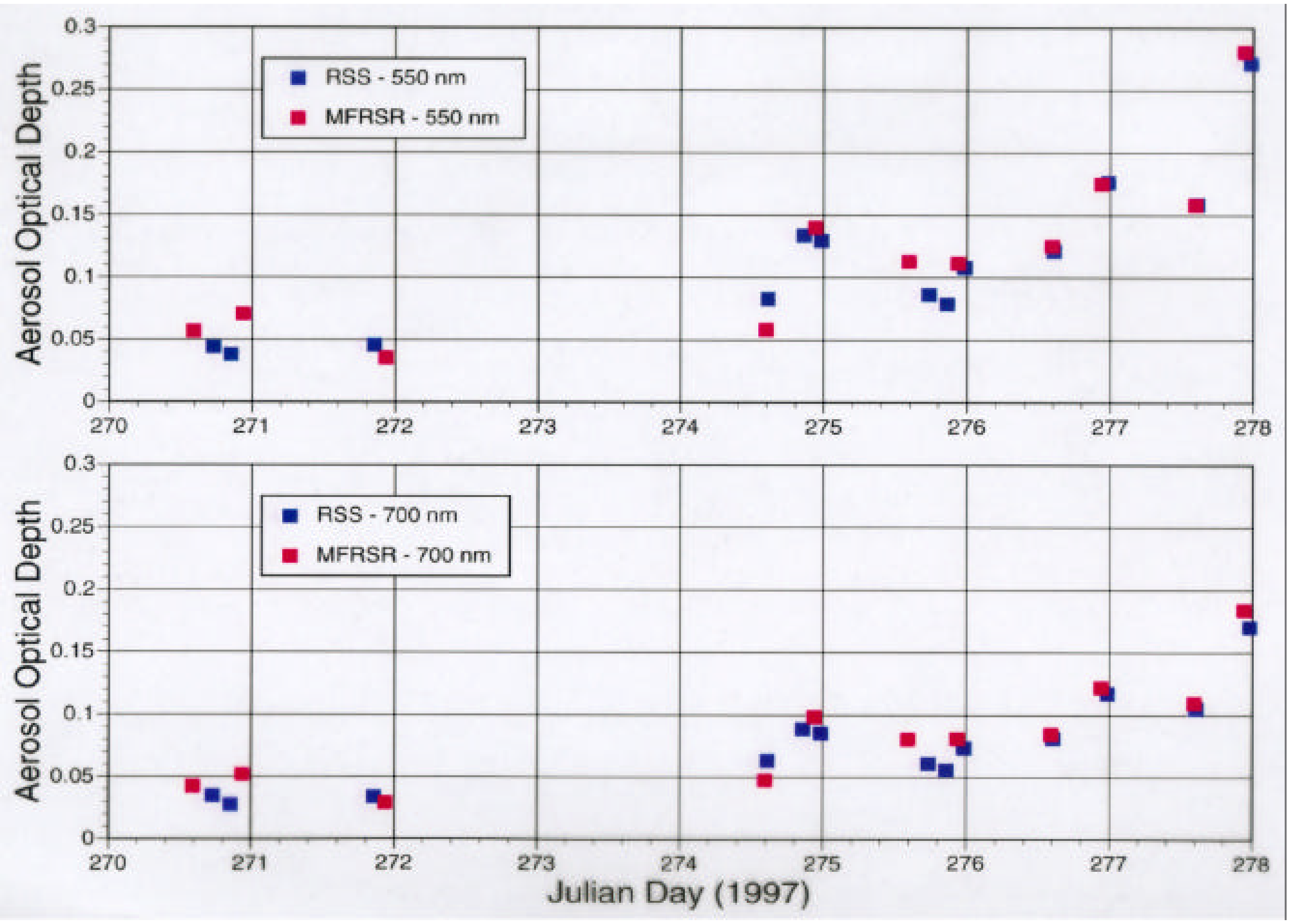


Figure 5. RSS/LBLRTM QME-derived Aerosol Optical Depths (blue) and MFRSR-derived AODs (red) referenced to 550 nm (top) and 700 nm (bottom) as a function of Julian Date over the time period September 27 - October 5, 1997.

In order to contribute to the discussion of anomalous absorption, the QME will be extended to the diffuse field using the CHARTS multiple scattering program (Moncet and Clough 1997). The use of the 1024-channel RSS will further assist in spectral assessments. Furthermore, model improvements borne out of this exercise will be incorporated into the rapid radiation model RRTM for use as the radiation scheme in GCMs.

Acknowledgments

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