Analysis of Rotating Shadowband Spectroradiometer (RSS) Data

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Introduction

The rotating shadowband spectroradiometer (RSS, shown in Figure 1) is our most recently developed instrument. It can be thought of as a 512-channel multifilter rotating shadow-band radiometer (MFRSR) spanning the wavelength range 360 nm to 1050 nm.[(a)] This portion of the shortwave spectrum represents about 75% of the sun's total energy. The RSS implements the same automated shadowbanding technique used by the MFRSR, and so it too provides spectrally resolved direct-normal, diffuse-horizontal, and total-horizontal irradiances, and can be calibrated in situ via Langley regression.

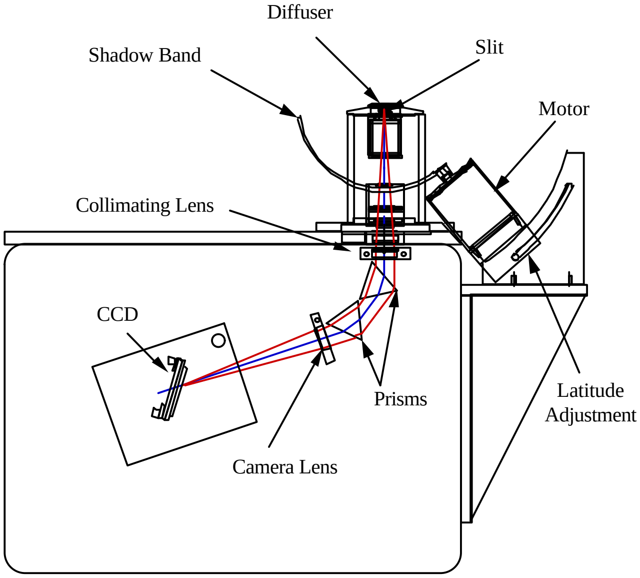

Figure 1. Cross-section of the RSS. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf*.)

Two RSS instruments were operated at the Southern Great Plains (SGP) Central Facility (CF) during the September 1996 H_2O Intensive Observation Period (IOP). This served as the maiden field campaign for this new instrument and an acceptance trial for routine operation as an Atmospheric Radiation Measurement (ARM) site instrument. The instruments were stable and reproducible to at least 0.3% in irradiance (the limit of stability of our calibrating standard) over the experiment period, with no statistically significant trend. Revisions were made to the first prototype after the IOP and subsequent analysis; long-term continuous RSS operation commenced at the SGP Cloud and Radiation Testbed (CART) site in July 1997. In this paper, we first describe calibration accuracy issues (both Langley and irradiance lamp) that we believe will be of interest to other users of ARM RSS data with particular emphasis on the 1997 Shortwave IOP, and then demonstrate photon pathlength retrievals.

Calibration and Optical Depths

The MFRSR and RSS instruments measure both direct-normal and horizontal surface irradiances, and intrinsically guarantee that all components share the same passbands and responsivities. Thus, Langley calibrations can be used as calibrations for the horizontal surface irradiances as well, producing self-consistent data for radiative transfer calculations. In the following discussion, we will try to show the interplay between the two methodologies, which these instruments can merge.

Harrison and Michalsky (1994) describe an objective Langley algorithm we use as the starting point for all our calibrations. A major operational issue for field sun-photometers is whether to depend on calibrations done at favorable high-altitude sites, in situ at the operating site, or perhaps both. While it might seem obvious that calibrations

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(a) The RSS optical resolution is nonlinear over the spectrum: for a 512-pixel instrument d/dpixel = 0.3 nm at 350 nm, 1 nm at 500 nm, broadening to ≈ 4 nm at 1 µm. We have an improved version in test at Atmospheric Sciences Research Center (ASRC) that doubles the number of pixels to 1024, with commensurate improvement in resolution.

"ought" to be done in the most favorable locations due to our wish to operate the RSS as a continuous ARM site instrument, our practice has been to achieve calibrations primarily by in situ Langley regression at the SGP. In the following discussion, we show that calibration precisions of ≈ 1% can be achieved there by Langley analysis of the returned data stream, given adequate instrument stability level for several months.

The starting point for any Langley calibration is an ensemble of "Langley events;" for each one obtains †, V_0, and some regression statistics for each measured passband. A typical "raw" optical depth spectrum taken by the RSS is shown in Figure 2. Rayleigh extinction can be subtracted and then O_3 removed, as described by Michalsky et al. (1995). The remaining structure is dominated by H_2O bands. Within these strong absorption bands, curve-of-growth causes Langley regression to fail; both † and V_0 are underestimated.

Figure 3 shows the V_0 variation from the mean in the RSS Langleys retrieved in situ at SGP, for selected pixels (which match MFRSR passbands but are narrower). The root mean square variability in this set, screened by our objective Langley algorithm, is ≈ 3%. Linear regressions show that the apparent "trends" are statistically insignificant compared to a 1-ß two-tailed floor determined by jackknife estimation.

Given no apparent drift, the simplest processing is to use any estimator of the central tendency (mean, median, or various weighting schemes for same) on the above to arrive at working calibrations for V_0. It should be emphasized that the variation in the V_0 intercepts does not stem from noise within the individual screened Langley regressions (given good instruments). There is a "paradox" that standard statistical estimators of the uncertainty of the regressed coefficients always underpredict the variance in V_0, compared to the event-to-event variation. Instead, this stems from the fact that false linear solutions to the Langley

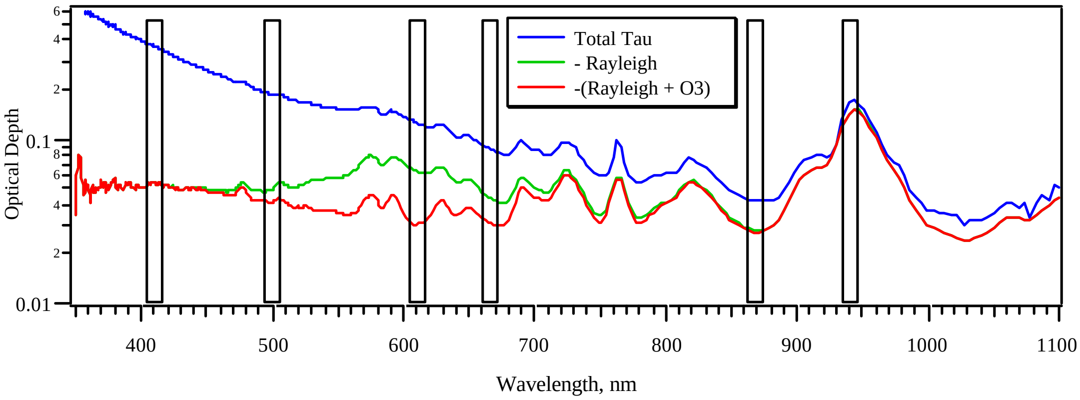

Figure 2. Typical clear-day optical depth spectrum (RSS) at SGP. (MFRSR passbands are marked by boxes). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf).*

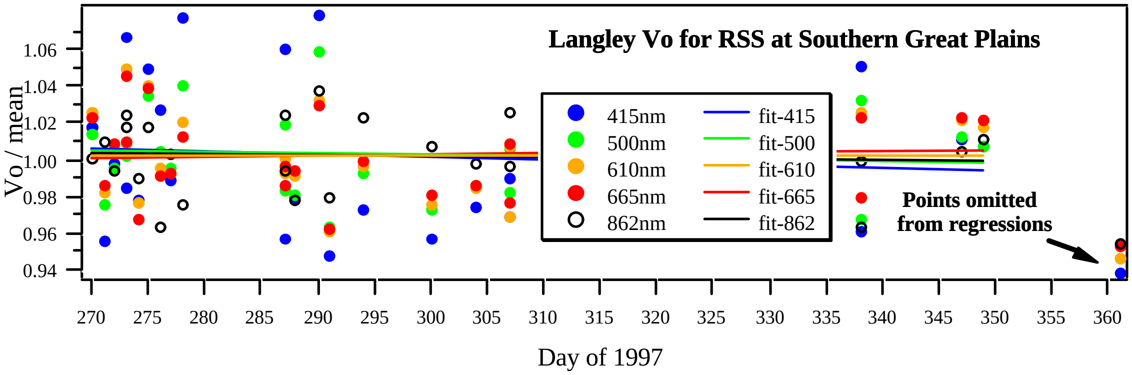

Figure 3. Ensemble statistics of an epoch of Langley V_0. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf).*

regression exist when the central assumption († invariant with airmass) is violated. If † = †* + b/m, where †* is independent of the airmass m, and b is an arbitrary coefficient, then the regression will be perfectly straight but the V_0 intercept will err.

Again, we want to emphasize that this calibration route, using our objective Langley algorithm followed by statistical examination and robustification of the V_0 series produced, is applicable to any sunphotometric data set. It can even be applied retrospectively, provided that the raw measurement time-series have been retained, if the instruments are operated continuously at a site for periods sufficiently long to obtain enough Langleys so that statistics converge, and instrument drift is tolerable. At typical continental sites such as the SGP where the variance in individual V_0 is ≈ 4%, then ≈ 25 Langleys are needed to drive expected uncertainties in V_0 below 1%, our usual working target. The "final" V_0 obtained from these data and applied to the Shortwave and H_2O IOP (September 1997) is shown in Figure 4. Note that the standard deviation/mean is <0.01 everywhere except the strong absorption bands (where this calibration is not meaningful) and the very shortest wavelengths.

If the RSS were only used as a sun-photometer this would be the end of the calibration effort, and we would argue that calibration uncertainty is ≈ 1%, leading to expected accuracies of optical depth of 0.01, assuming there aren't unknown systematic errors. However, surface spectral radiometry, and better yet, the ability to obtain optical depths and surface spectral fluxes from one instrument, is the raison d'être of the MFRSR and RSS instruments, so how are we doing?

ARM provided a LiCor 1800 portable calibrator during the Fall 1997 IOP. This is a tertiary 200 W Tungsten-Halogen source with a quoted accuracy of 4%. (Laboratory comparisons of this irradiance standard vs. others done subsequent to the IOP are discussed by Michalsky et al. 1998). Responsivities (V/[W/m^2/nm]) measured against this LiCor source can then be applied to the V_0 from Figure 4 to produce "our" inferred extraterrestrial irradiance spectrum. While no one would contemplate using either this irradiance calibrator or the SGP site to make a definitive effort at measuring I_0(¬), it is instructive as a closure experiment to compare the results with published extraterrestrial spectra. The results are shown in Figure 5; the agreement is better than 5% everywhere the Langley extrapolations are valid and 1% at wavelengths > 600 nm. The latter is surely happenstance, and the former is well within the combined uncertainties of the LiCor calibrator and uncertainties about the true extraterrestrial spectrum.

In Figure 6 we show data comparing aerosol optical depths retrieved by the RSS and the AATS sunphotometer.(a) It is a carefully characterized conventional interference-filter sunphotometer with an extensive history of high-altitude calibrations. The data shown are from one of the clearer days seen during the 1997 IOP; the top panel shows the data as they were presented at the Instantaneous Radiative Fluxes (IRF) working group meeting, the bottom after subsequent corrections by both instrument groups.(b) Both before and

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(a) Developed and operated by Drs. P. Russell and B. Schmid of NASA Ames Research Center.

(b) Our corrections stemmed from an angular-correction file which was reversed east to west.

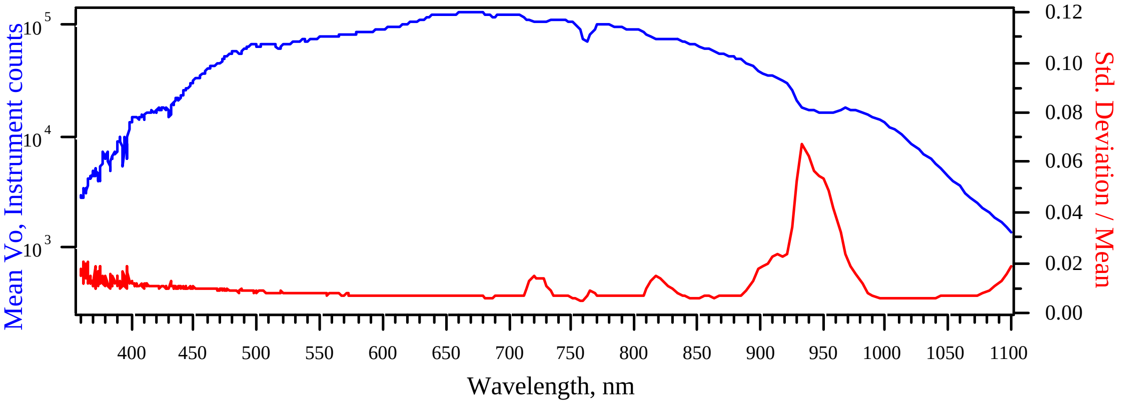

Figure 4. Robust V_0 for RSS #103 from multiple Langleys at SGP, Fall 1997. (For a color version of this figure, please see *http://www.arm.gov/docs/ documents/technical/conf_9803/harrison-98.pdf).*

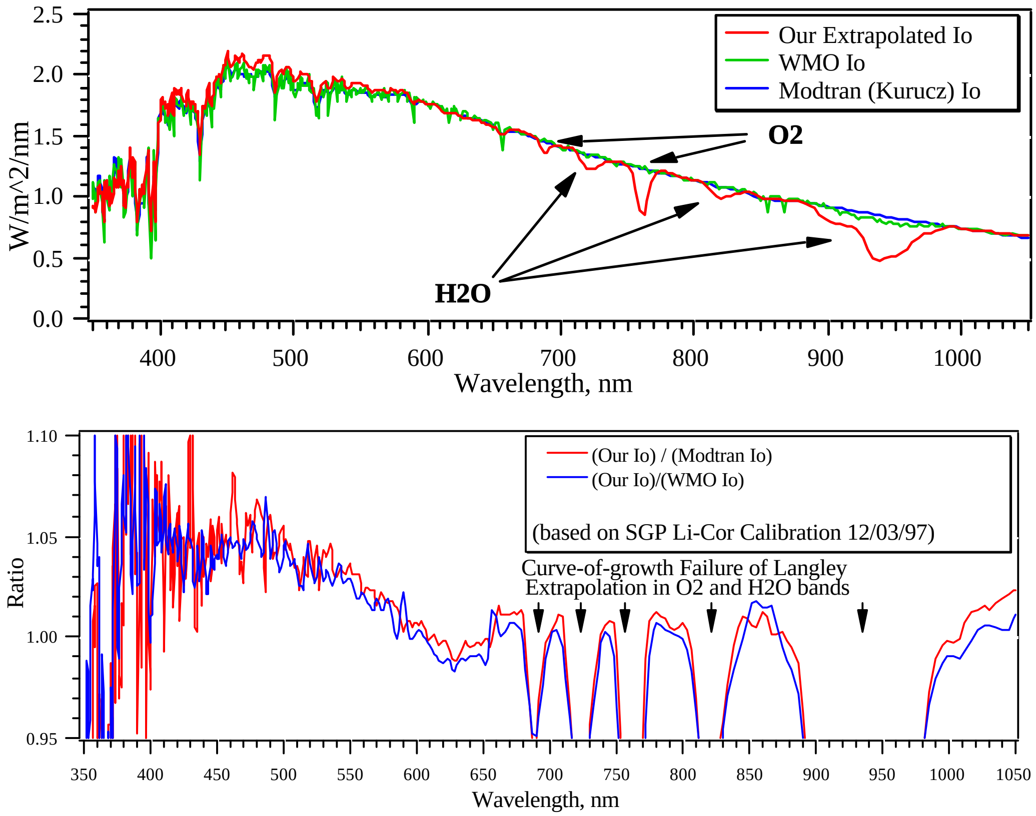

Figure 5. Extrapolated LiCor irradiances at SGP vs. published spectra (top), ratios of same (bottom). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf).*

after the corrections, the bias between the two is comparable to our quoted statistical limit of 0.01 optical depths (1 ß) alone. After the corrections, the 451-nm and 525-nm passbands agree to ≈ 0.008 worst-case, the 864 to 0.01, and the 380-nm channel to 0.02 worst-case, late in the day. The trends in the data through the day may be evidence of a remaining small systematic error on our part, which we continue to study.

These data represent a test of optical depth retrievals by two completely independent systems: differing instruments, calibrations, and data reduction algorithms. In this light the agreement is remarkable. For the present, we believe 0.01 optical depth accuracies are near the state-of-the-art; below this threshold, many systematic instrumental and analysis issues that could previously be ignored become important. Yet, for climate research, we would like to have better accuracies, and this will require unknown effort to achieve.

Clear Sky Irradiances and Direct/Diffuse Ratios

In Figure 7, we show data taken with the RSS near solar noon on September 29, 1997, at SGP. This was the clearest day during the IOP (with aerosol optical depths at 525 nm of 0.035 to 0.04 through the day), and hence will likely be used widely for various tests of models vs. measurements. We show these data to demonstrate what the RSS can do to help such efforts, but also as a cautionary note for those interpreting the many other measurements available.

In the top panel of Figure 7, the RSS direct-normal and diffuse spectral irradiances using calibrations from the ARM LiCor 1800 are compared to MODTRAN 3.5 computations using its standard rural aerosol parameterization and no aerosol (Rayleigh). For the first of these, aerosol

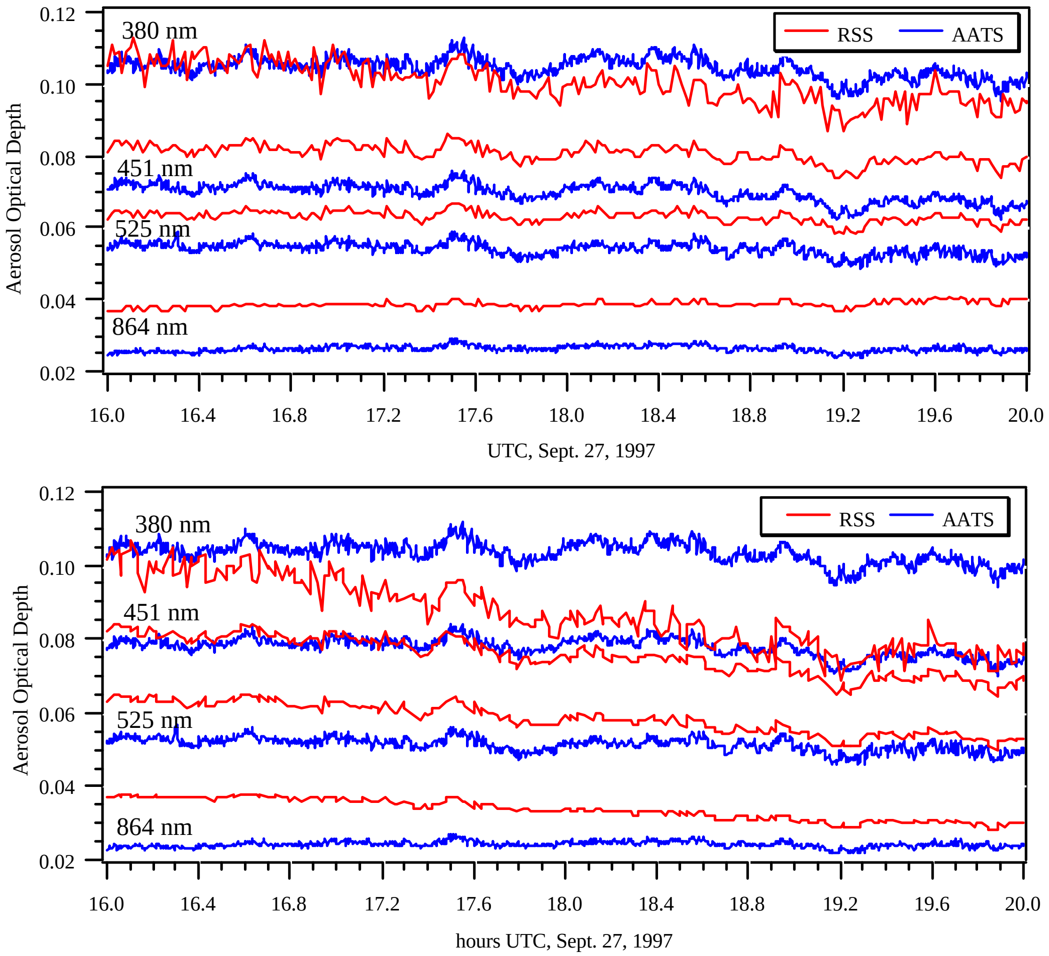

Figure 6. RSS and AATS-6 sunphotometer aerosol optical depths at SGP. (Top) data as presented at IRF meeting, (bottom) after subsequent corrections to both AATS and RSS data. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf).*

optical depths vs. wavelength were assigned from an Ångstrom fit to MFRSR direct-beam-derived aerosol optical depths for independence. With the logarithmic ordinate, no discrepancies are apparent in the direct-normal; modest discrepancies are in fact present, but are entirely attributable to the relationship of the irradiance scale derived from the LiCor calibrations and the model's extraterrestrial irradiance as discussed in Figure 5.

The diffuse-to-direct ratios are more interesting. Note that these are independent of calibration for a MFRSR or RSS. As is apparent from these data (and the percent difference shown in the lower panel), the diffuse sky irradiance lies between that predicted by the model using the rural aerosol parameterization and a Rayleigh sky at all wavelengths, approaching the model with its rural aerosol parameterization at the longest wavelengths and being very close to the Rayleigh prediction at 360 nm. While space does not permit detailed discussion of interpretation, these results are consistent with a modestly lower aerosol single-scattering albedo than that assumed by the model.

Mean Photon Pathlengths from O_2 A-Band

The RSS has sufficient resolution that we can obtain a measurement of the "mean" photon pathlength using the O_2 A-band absorption as described by Harrison and Min (1996). Given the modest resolution of the RSS, we can retrieve only a particular mean (with very high resolution more information can be retrieved), and its precise definition is the mean of the first moment of the geometric

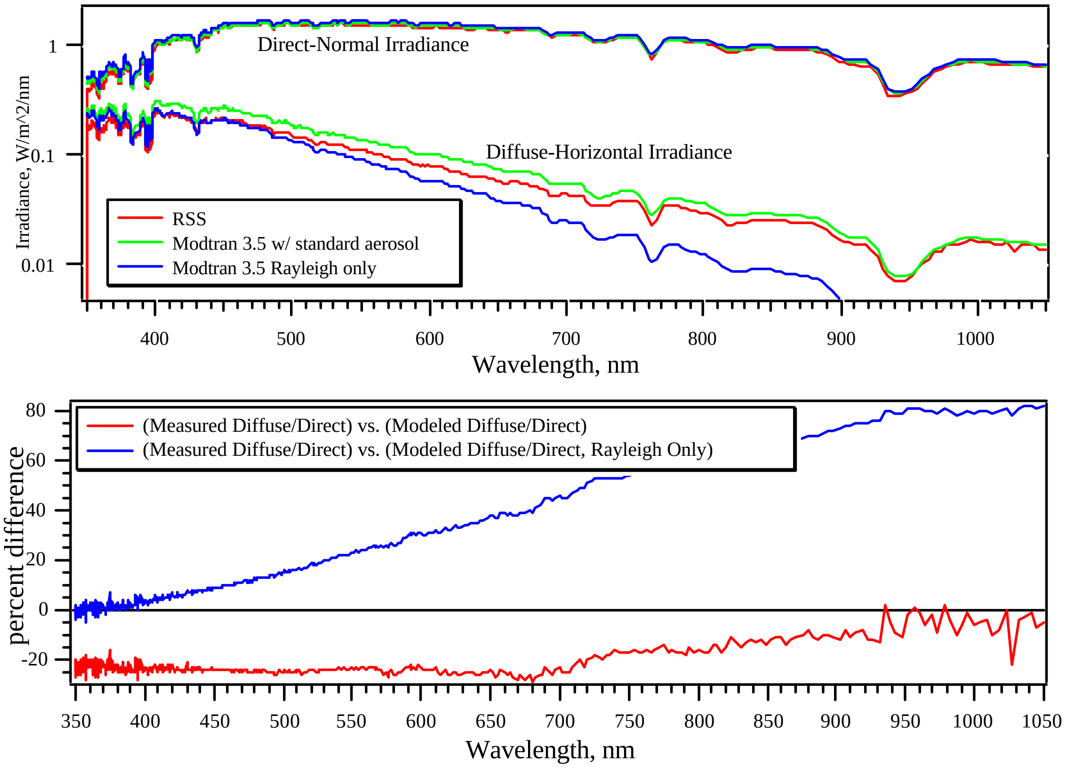

Figure 7. Clear-sky data from September 29, 1997, at SGP. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf).*

pathlength with respect to pressure, and the inverse ½-power moment with regard to temperature, arising from the Lorentzian line-profile

$$k_i = \frac{S_i}{\pi}\frac{\alpha_i}{(\upsilon - \upsilon_i)^2 + \alpha_i^2} \quad \text{where} \quad \alpha_i = \alpha_i^0 \frac{p}{p^0}\left(\frac{T^0}{T}\right)^{1/2}$$

The result is naturally expressed in atmospheres. In Figure 8, we show computed direct-beam transmissions using MODTRAN 3.5 for pixels in the RSS spectrum from outside the A-band to the center (the RSS does not have sufficient resolution to resolve the two branches), versus measured clear-sky transmissions as a function of airmass. These calculations are very sensitive to instrument slit-function and band-model; given this, the agreement is very good. In any event, the data of Figure 8 serve as an empirical calibration for RSS-derived photon pathlengths.

The photon pathlength, together with the cloud optical depth and mean effective droplet radius, describe the optical properties of the warm cloud system and provide strong constraints on geometric properties that may otherwise be unknown. The cloud optical depths and mean droplet radii can be obtained from either MFRSR or RSS data, and a microwave radiometer (Harrison and Min 1996). In Figures 9 and 10, we show these RSS-retrieved quantities for a "textbook" single-layer stratus case at SGP. We emphasize that the low scatter in the pathlengths seen in this case is due to the horizontal homogeneity of this system, and its invariant physical depth through the day. We believe that long-term studies of the joint-statistics of these retrieved parameters will permit us to test the accuracy of the cloud-diagnostic equations used by GCMs and to improve our understanding of cloud climatology.

References

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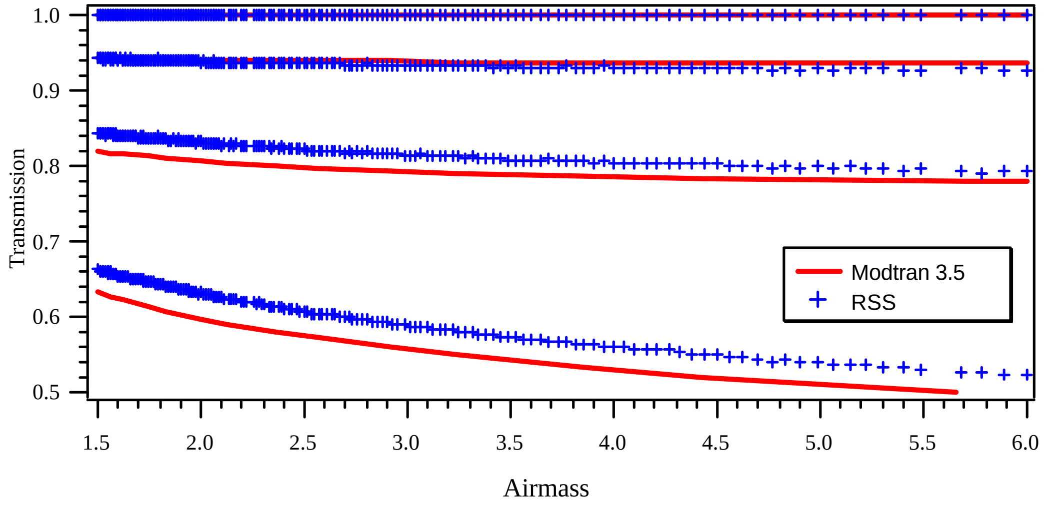

Figure 8. Clear-sky direct-beam transmissions, 4 pixels in the O_2 band. (For a color version of this figure, please see *http://www.arm.gov/docs/ documents/technical/conf_9803/harrison-98.pdf).*

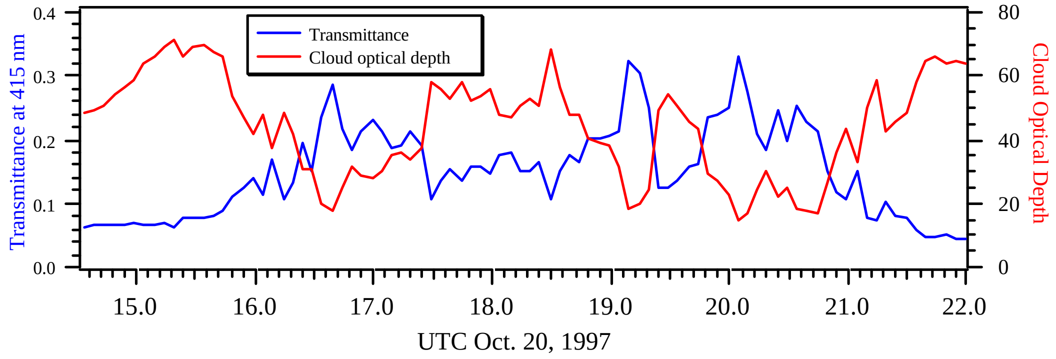

Figure 9. A day of nearly uniform stratus at SGP. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf).*

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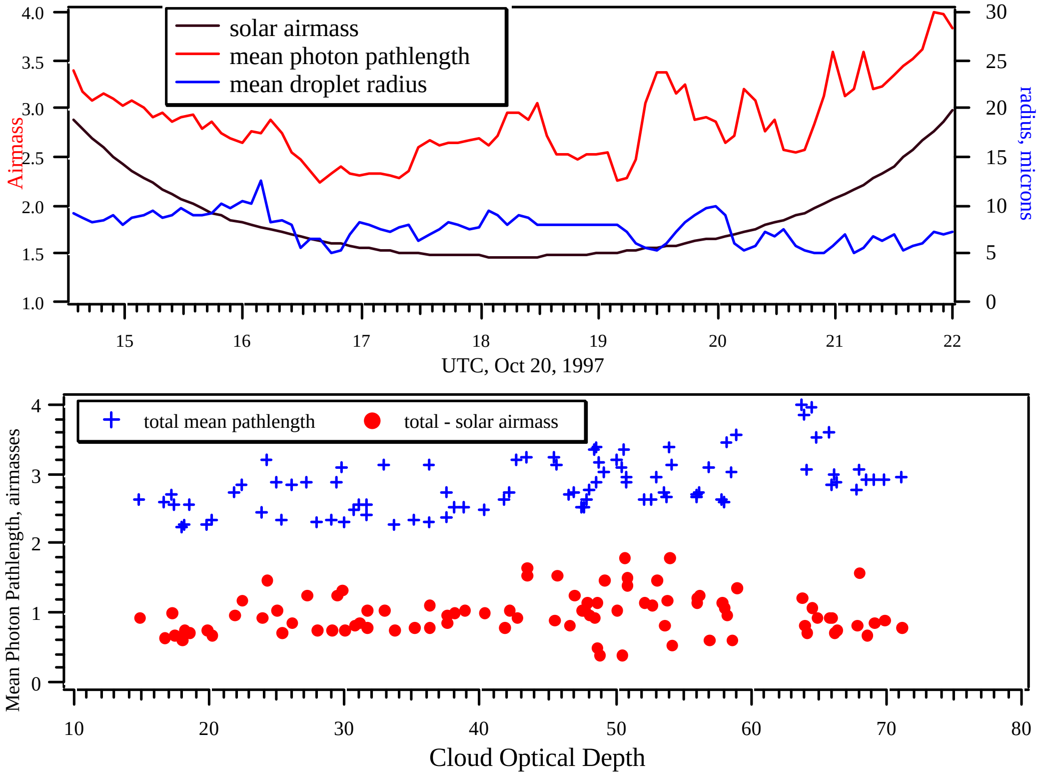

Figure 10. Photon pathlengths in a day of nearly uniform stratus at SGP. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/harrison-98.pdf).*