The Rotating Shadowband Spectroradiometer (RSS) at SGP

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Abstract. The RSS provides continuous spectral measurements of total-horizontal, diffuse-horizontal, and direct-normal irradiance from 360 to 1100 nm using the automated shadowband technique. We show instrument performance, calibration method and accuracies, case data from the first-generation instrument operated at the Southern Great Plains (SGP) site, and comparisons with the improved design now starting operation.

Introduction

The Rotating Shadowband Spectroradiometer (RSS) couples a CCD spectrograph (512 pixels in the first-generation design, 1024 in the second) spanning the wavelength range 360 to 1100 nm with the shadowbanded fore-optic developed for the Multi-Filter Rotating Shadowband Radiometer (MFRSR, Harrison et al., 1994). The RSS provides spectrally-resolved direct-normal, diffuse-horizontal, and total-horizontal irradiances using the automated shadowbanding technique developed for the MFRSR. The three components are guaranteed to have the same passbands and responsivities; thus Langley calibrations can be used for the horizontal surface irradiances as well, producing self-consistent data for radiative transfer calculations.

Two 1st-generation RSS instruments were operated at the Southern Great Plains (SGP) central facility of the Atmospheric Radiation Measurement (ARM) Program during the September 1996 H_2O Intensive Observation Period (IOP); this served as the first field campaign for this new instrument. Long-term operation of a single 1st-generation RSS started at SGP in August, 1997, for the 1997 IOP. The 2nd-generation instrument has significant improvements and was deployed subsequently to SGP; we show comparative laboratory and field data.

Optical Depths, Langley Calibrations

The RSS is operated continuously at the SGP facility; calibrations for sun-photometry are derived from the data using an objective Langley algorithm developed by Harrison and Michalsky [1994]. This differs from the more common practice of periodically transporting sun-photometers to favorable high-altitude sites. Here we show that calibration precisions of ≈ 1% can be achieved at sites such as SGP by Langley analysis of in-situ data, given adequate instrument stability for several months.

The starting point for any Langley calibration is an ensemble of "Langley events;" from each an optical depth τ, an uncalibrated extraterrestrial instrument response V_0, and associated regression statistics are obtained for each measured passband. A typical Langley optical depth spectrum taken by the RSS is shown in figure 1. Rayleigh extinction can be subtracted and then O_3 removed as described by Michalsky et al. [1995]. Most of the remaining structure is dominated by strong absorption bands of H_2O and O_2. Within these bands curve-of-growth causes Langley regression to fail; both τ and V_0, are underestimated. An incremental optical depth due to an O_2-O_2 collisional band (Pfeilsticker et al. 1997) is marked; Michalsky et al. [1999] discuss RSS measurements of O_2-O_2 absorption.

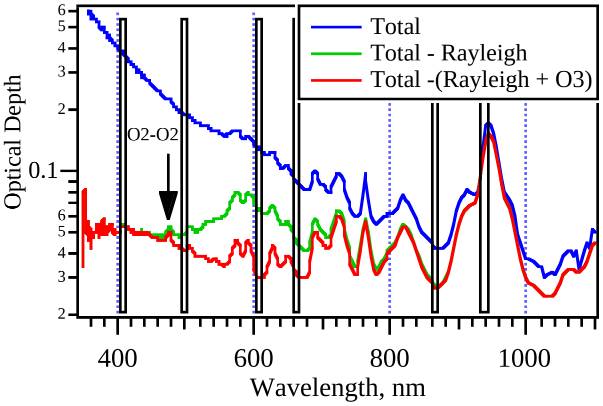

Figure 1. Langley RSS Optical Depth Spectrum from SGP. (Standard MFRSR passbands are marked by boxes)

Figure 2 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 RMS 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-σ two-tailed floor determined by jackknife estimation.

Given no apparent trend any estimator of the central tendency (mean, median, or various weighting schemes for same) of the ensemble of V_0 yields a working calibration. The variation in the individual V_0 intercepts *does not* stem from noise within the individual screened Langley regressions (given good instruments). Instead false linear solutions to the Langley regression exist when the central assumption (τ invariant with airmass) is violated.

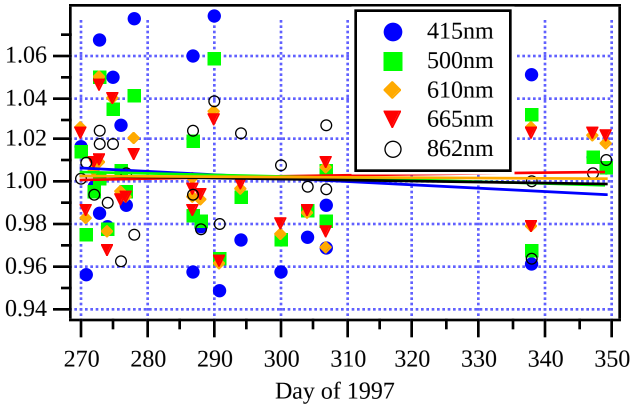

Figure 2. Ensemble statistics of Langley V_0 ratios at SGP

At typical continental sites such as 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 Intensive Operation Period (Sept. 1997) is shown in figure 3. The standard deviation/mean is < 0.01 everywhere except the strong absorption bands (where this calibration is not meaningful) and the very shortest wavelengths.

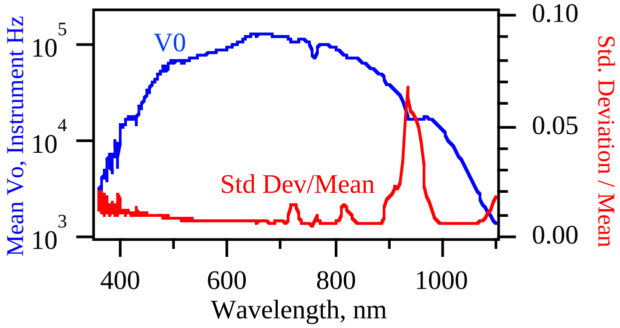

Figure 3. Robust V_0 for RSS # 103 at SGP

ARM provided a LI-COR 1800-2 portable calibrator during the Fall '97 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 Kiedron et al., 1999.) Responsivities (Hz/(W/m^2/nm)) measured against this LI-COR source can then be applied to the V_0 from figure 3 to produce "our" inferred extraterrestrial irradiance spectrum. While no one would contemplate using either this irradiance calibrator or the Southern Great Plains site to make a definitive effort at measuring $I_0(\lambda)$, it is instructive as a closure experiment to compare the results with published extraterrestrial spectra. The results are shown in figure 4; 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 LI-COR calibrator and uncertainties about the true extraterrestrial spectrum.

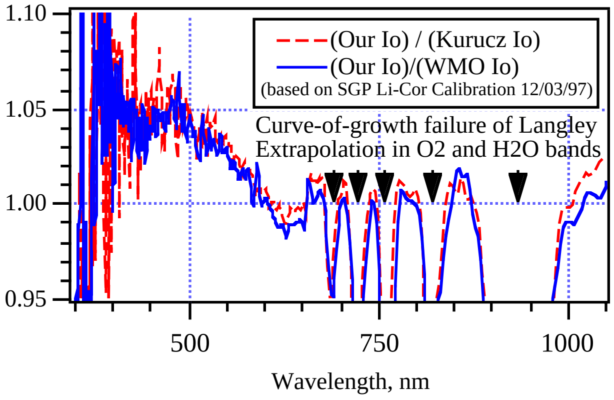

Figure 4. Ratios of extrapolated TOA irradiances vs. published spectra

Several groups intercompared sun-photometric measurements of aerosol optical depths (τ_{aer}) during the 1997 Shortwave IOP. A formal report remains in preparation, but preliminary results as they apply to the 1st-generation RSS will be described here briefly. Comparisons with the AATS and CIMEL conventional sun-photometers (operated by Dr. B. Schmid and R. Halthore respectively) on several clear days, particularly Sept. 27 where τ_{aer} was ≈ 0.05 at 500 nm (remarkably low for SGP) and stable through the day, demonstrated biases between the RSS and the other instruments comparable to *our* quoted statistical limit of 0.01 optical depths (1 σ) alone. Against the AATS the 451 and 525 nm passbands from the RSS agree to ≈ 0.008 worst-case, the 864 to 0.01 and the 380 nm channel to 0.02 worst case.

Our optical depths at all wavelengths trend downward through the day, where those measured by the AATS decline less. We attribute these differences at all wavelengths other than 380 nm to a very small east-west leveling tilt of the RSS in the field, or comparable small errors in the laboratory measurement of the fore-optic angular response. The discrepancy for all except the 380 nm comparison is less than 0.003 trend through the day.

The downward trend in our 380 nm measurement is not explained by a tilt congruent with the longer wavelength data. While nominally within our expected error bar from figure 3, the trend is potential evidence of small systematic error at short wavelengths we do not yet fully understand. It may be out-of-band rejection limitation; the 2nd-generation instrument is improved in this regard and we are waiting to see if its results are better.

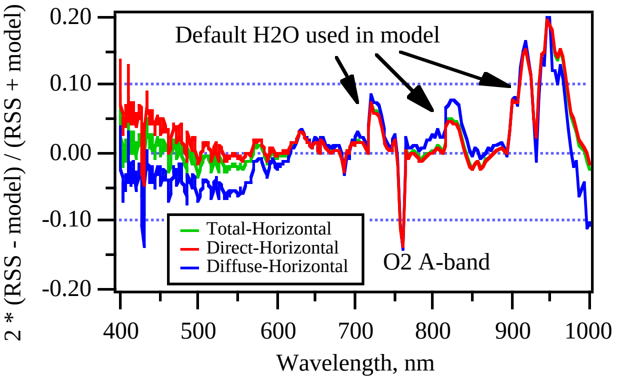

Figure 5. MODTRAN 3.7 with "urban aerosol" parameterization vs. RSS measurements, Albany NY

We emphasize that this comparison represents a test of optical depth retrievals by *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 absolute accuracies are near the state of the art; below this threshold many systematic instrumental and analysis issues that could previously be ignored become important.

Direct/Diffuse/Total Spectroradiometry

Figure 5 shows modeled vs. measured clear-sky results taken 16:39:00 UTC Nov. 4, 1996 in Albany NY with the prototype instrument shortly after it returned to our laboratory from the 1996 IOP. We had no independent H_2O column measurement, and simply ran the model with its default. Here the agreement is good given that the model's "urban aerosol" parameterization is applied; this assumption is conventional for data from Albany.

In figure 6 we show data taken with the RSS near solar noon on Sept. 29, 1997 at SGP. This was the clearest day during the 1997 Shortwave IOP (with aerosol optical depths at 525 nm of 0.035 to 0.04 through the day), and hence the most stringent test of clear-sky properties available to us to date. In the bottom panel the RSS diffuse spectral irradiance (calibration from the ARM LI-COR 1800) are compared against MODTRAN 3.7 computations using its standard rural aerosol parameterization and no aerosol (Rayleigh). Aerosol optical depths vs. wavelength were assigned from an Angstrom fit to MFRSR direct-beam-derived aerosol optical depths for independence. Direct-normal irradiances are not shown; the discrepancies are small, and attributable to the relationship of the irradiance scale derived from the LI-COR calibrations and the model's extraterrestrial irradiance as discussed in figure 4.

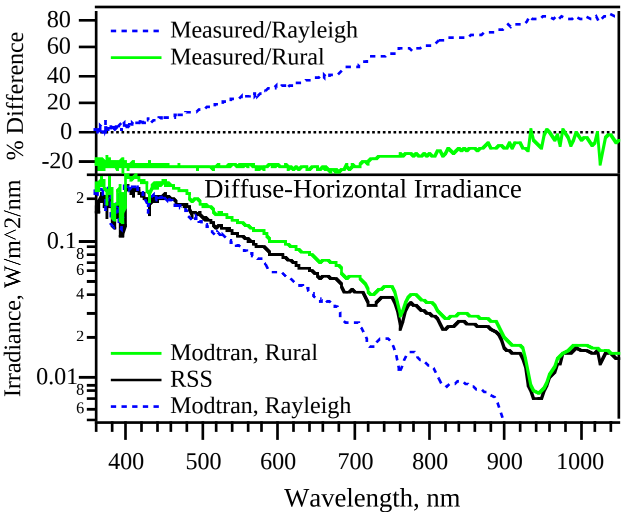

Figure 6 . Clear-Sky Data from Sept. 29, 1997 at SGP

The spectral diffuse-to-direct ratios are shown in the top panel of figure 6. These ratios are independent of calibration for a MFRSR or RSS. 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 close to the Rayleigh prediction at the shortest. Measurements below 400 nm should however be viewed with some caution as these data may be affected by stray light. This looks like a modest "clear sky anomaly" as suggested by Arking [1996] and Kato et al. [1997]; integration over the spectrum yields a deficit of ≈12 W/m^2 in the diffuse irradiance from the model calculation using the rural aerosol parameterization.

We do not wish to make too much of a single case, and truly clear sky events with low aerosol optical depths are rare at SGP. When aerosol optical depths are greater the modeled results can easily be fitted to the data by varying the single-scattering albedo and scattering phase functions within plausible ranges in the absence of measurements aloft to constrain these important parameters. Nonetheless the spectral signature of the "diffuse anomaly" seen in the top panel of figure 6 is bland and increases to shorter wavelengths. This is strongly suggestive of an aerosol, not a gas as hypothesized by Halthore et al. [1998]. Further, given that these events are so rare, it would not be surprising that the aerosol properties seen at SGP are unusual as well for these cases. We can gain information as more cases are collected; if the spectral signature varies from case to case then causation by gas absorptions would be ruled out, leaving only unusual aerosols or failure of the model as mechanisms. Measurements of aerosol optical properties aloft would of course go a long way to settle this issue, but are hindered by the rarity of suitable skies, and the difficulty of measuring the aerosol single-scattering albedo.

Instrument Improvements

In July 1998 we deployed a substantially-revised RSS instrument to SGP. The enabling improvement that permitted a rethinking of other instrument tradeoffs was the substitution of a state-of-the-art 1024 x 256 pixel astronomical-grade open-polysilicon CCD array for the Hammamatsu NMOS 512-pixel linear array used in the 1st-generation RSS. Optical design issues and results will be presented elsewhere; here we show only comparisons of the 2nd-generation instrument with the earlier design.

In figure 7 we compare data taken side by side by the old and newer instruments at SGP to show the excellent radiometric agreement of the two instruments and the substantially better resolution of the newer one. (Both were calibrated from the same transfer standard.) The structure seen in the data from the improved instrument (particularly evident at shorter wavelengths) is reproducible and confirmed by comparisons against MODTRAN.

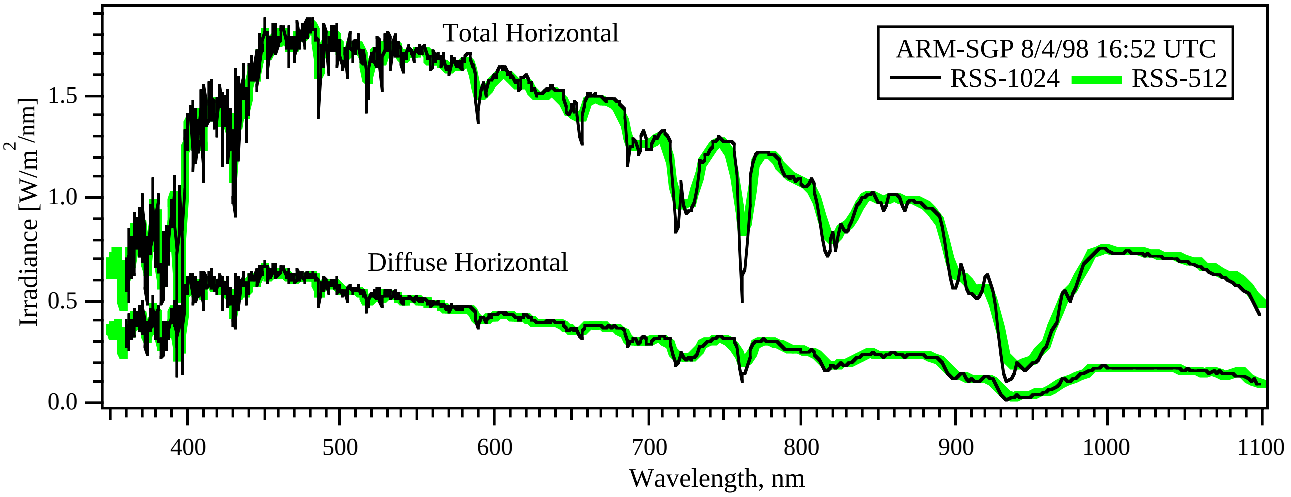

Figure 7. Comparison of simultaneous observations, revised RSS vs. original

We hope that readers will particularly note the agreement of these two measurements at the wavelength extremes in the diffuse irradiance, where signal-to-noise is challenged by the subtraction method used to obtain the diffuse, and out-of-band rejection and dynamic range concerns are most severe. This agreement demonstrates that the data from the 1st-generation RSS are usable for all but the very most demanding tasks. The photon pathlength retrievals shown by Min and Harrison [1999] support this.

Nonetheless the new design is much better radiometrically as well as simply having higher resolution. In figure 8 the slit-scattering functions of the two instruments measured against three laser lines are shown, the newer instrument with bold lines and the older dotted. The newer instrument achieves far-out-of-band rejections of 10^{-6}: an order of magnitude better than the older instrument. (It in turn is superior to most single-grating spectrographs, which typically achieve 10^{-4})

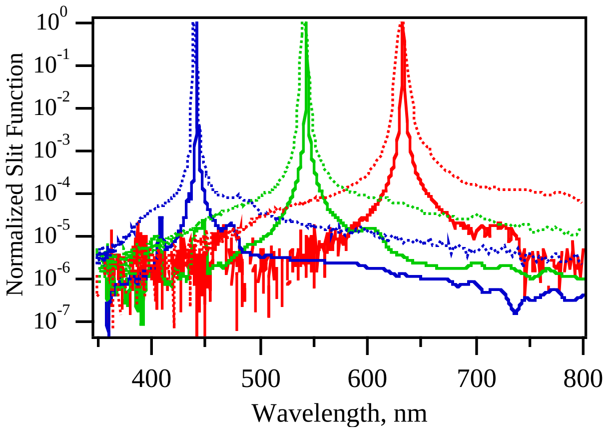

Figure 8. Instrument slit-scattering functions

With the much higher responsivity of the new arrays we can also afford to "throw away" light, even after the reduction and slitwidth and numerical aperture that produce the improvement seen in figure 8. The new design uses two thin glass absorption filters to intentionally decrease responsivity in the 500 - 670 nm range where the product of solar output and system responsivity otherwise produces a strong maximum. This compresses dynamic range as shown in figure 9, and reduces out-of-band light contributions at the wavelength extremes.

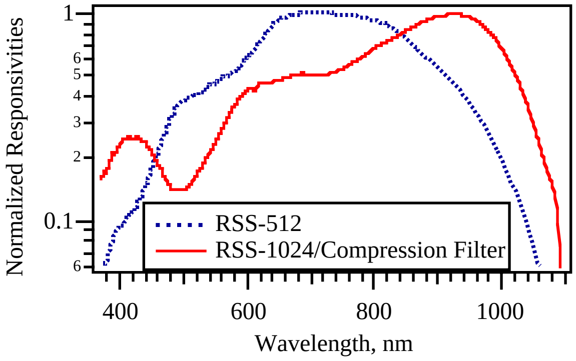

Figure 9. Normalized Instrument Responsivities

In Conclusion

In this letter we have described the performance of both the original RSS and our improved version, and a wide range of observations made at SGP with them. Further work continues, and we have just deployed an instrument to Barrow, AK. We believe that the spectrally-resolved direct/diffuse/total-horizontal irradiances the RSS instruments provide will help address current problems in atmospheric radiation, and provide the starting point for a variety of useful inversions for remotely-sensed parameters.

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