HYPERSPECTRAL SOLAR RADIOMETRY FOR SURFACE REFLECTANCE RETRIEVAL

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1. Introduction

Currently, one of the largest sources of errors in the retrieval of apparent surface reflectance is incomplete knowledge of the atmosphere at the time of an AVIRIS overpass. The most common method of extracting atmospheric parameters at the time of data acquisition is the measurement of optical depth (τ). These measurements are typically made with a solar radiometer such as the Reagan instrument (Ehsani et al 1998); a filter based radiometer with ten channels in the visible/near infrared. The measured optical depths are incorporated in an atmospheric radiative transfer model such as ATREM (Gao et al 1993) or MODTRAN (Berk et al, 1989) to improve the estimate of scattering present in the scene (Green, 1993). Ancillary satellite data has also been used to improve the estimate of ozone (Green, 1998). Finally, if a large spectrally uniform target is available, a ground reflectance calibration is undertaken. The ratio of the measured to model retrieved reflectance (a residual spectrum) is applied across the scene to remove errors primarily associated with the transmission term in the surface reflectance retrieval (Clark et al 1995). Field experience has shown that suitable ground targets, large and highly uniform such as playas, are nearly impossible to find outside the desert environment. With this in mind, we have undertaken an investigation into the use of an ASD Full Range Spectroradiometer (ASD-FR) (www.asdi.com) as a "hyperspectral" solar radiometer. Spectral measurements of optical depth should improve the parameterization of scattering and ozone. In addition to better atmospheric parameterization, it also may be possible to apply a residual spectrum directly to the transmission term in the surface reflectance retrieval.

2. Radiometry

Solar radiometers depend on a radiometrically stable system of detectors and electronics. Typically a calibration experiment is performed at a high mountain site to determine the top of the atmosphere (TOA) instrument response via the Langley method. Once the calibration of the intrument is established, a stable radiometer can be deployed to make instantaneous measurements of optical depth. Recent improvements to the ASD-FR's temperature and dark current stability have dramatically improved the radiometry of the instrument as shown in a series of laboratory calibrations (Figure 1.). 42 laboratory calibrations are shown on the left plot, On the right hand side the percent standard deviation is calculated for all 42 calibrations (January 1999 – September 1999) as well as for 14 calibrations during the summer of 1999 when the instrument was in nearly constant use.

3. Instrument Design

Solar radiometers typically consist of: a telescope to narrow the field of view (FOV) of the incident radiation to only that from the sun's disk, a series of detectors with filters to restrict the wavelengths incident on the detectors, a method to track the sun very accurately as it traverses the sky, and a data recording and control system. We have designed a simple telescope consisting of a front and rear aperture to restrict the FOV to 2°. The telescope only serves to restrict the FOV and does not contain lenses or mirrors. At the rear of the telescope a two-inch Spectralon™ integrating sphere with a fiber optic port is mounted. The integrating sphere provides diffuse uniform illumination for the fiber optic to view. In addition, the sphere should reduce the effects of tracking errors as long as the sun's disk, about 0.5°, is kept within the 2° FOV of the instrument. On the top of the telescope is a pinhole and target to allow the operator to accurately align the telescope with the sun's disk. The telescope is mounted on a simple manual elevation and azimuth control allowing precise pointing at the sun. The telescope was designed so that it could also easily be attached to a commercially available solar tracker such as the Kipp and Zonen 2AP. A personal computer controls the ASD spectroradiometer and records the spectra on a hard drive.

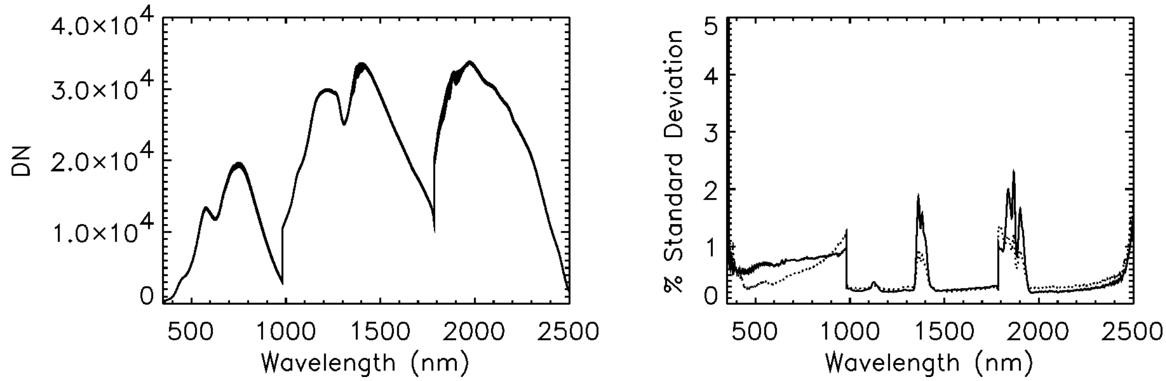

Figure 1. Forty-two calibrations for the ASD-FR performed from January to September of 1999 are shown on the left. Percent standard deviations are plotted on the right, the solid line is all calibrations, the dotted line is for fourteen calibrations conducted during the summer of 1999 when the instrument was in near constant use.

4. Side by Side Experiment with Reagan Instrument

Currently, the "industry standard" instrument in the AVIRIS community is the Reagan solar radiometer (Ehsani et al 1998). A series of side by side experiments were done to determine the agreement between this well-established instrument and the ASD-FR. The Reagan instrument has 10 channels centered at 380, 400, 440, 520, 610, 670, 780, 870, 940, and 1030nm. The approximate bandpass for each channel is 10nm FWHM, and the FOV is 3.2°. Three days (sunrises) were collected at the Table Mountain Observatory north of Boulder, Colorado. The data were fit over an airmass range of 8 to 2 for each day. Airmasses were determined with Kasten's table (Kasten and Young 1989). The results for the three experiments are shown in Figure 2 in the left column. The continuous spectrum is the ASD-FR measurement; the diamonds are the optical depths determined for the ten Reagan channels. The overall agreement is excellent with most differences in the third decimal place of optical depth. Deviations are present at the shortest wavelength and may be due to differences in the small diffuse (scattered) component as seen by instruments with different FOVs. The large difference at 670nm is a problem in the Reagan, as the Langley plots show a distinct departure (break) from a straight line. The differences in the water vapor channel are probably due to the high sensitivity to the filter function of the instrument to the strong absorbing lines present in the 940nm water vapor band. The right column in Figure 2 are individual plots for three different channels for the three days, showing the very similar fits to a straight line.

5. Determination of Valid Langley Channels

The Langley method of calibration is only valid in channels that follow the Beer-Bouguer-Lambert law. The presence of saturated lines in strong absorption bands (e.g. water vapor, oxygen, carbon dioxide…) invalidates the Langley method for large portions of the solar spectrum. To determine where Langley was strictly valid we simulated a high mountain calibration experiment with the radiative transfer code MODTRAN4.0, creating a series of synthetic Langley plots. MODTRAN was run in direct solar irradiance mode, with elevation angles corresponding to 15 airmass to 1 airmass (90^{o} elevation) evenly spaced in airmass (Figure 3). The model irradiances were resampled to ASD-FR wavelengths and resolutions, and a straight line fit between the airmass and ln(irradiance) performed. The Langley extrapolated TOA solar spectrum was then compared with to the model input TOA solar spectrum to determine the valid channels. We consider channels that recreate the TOA solar spectrum to +/- .5% to be valid Langley channels. In this analysis, 379 of 2151 (18%) channels in the ASD-FR were found to be valid. Valid channels are found throughout the entire wavelength range including a few channels in the 2000nm to 2500nm range.

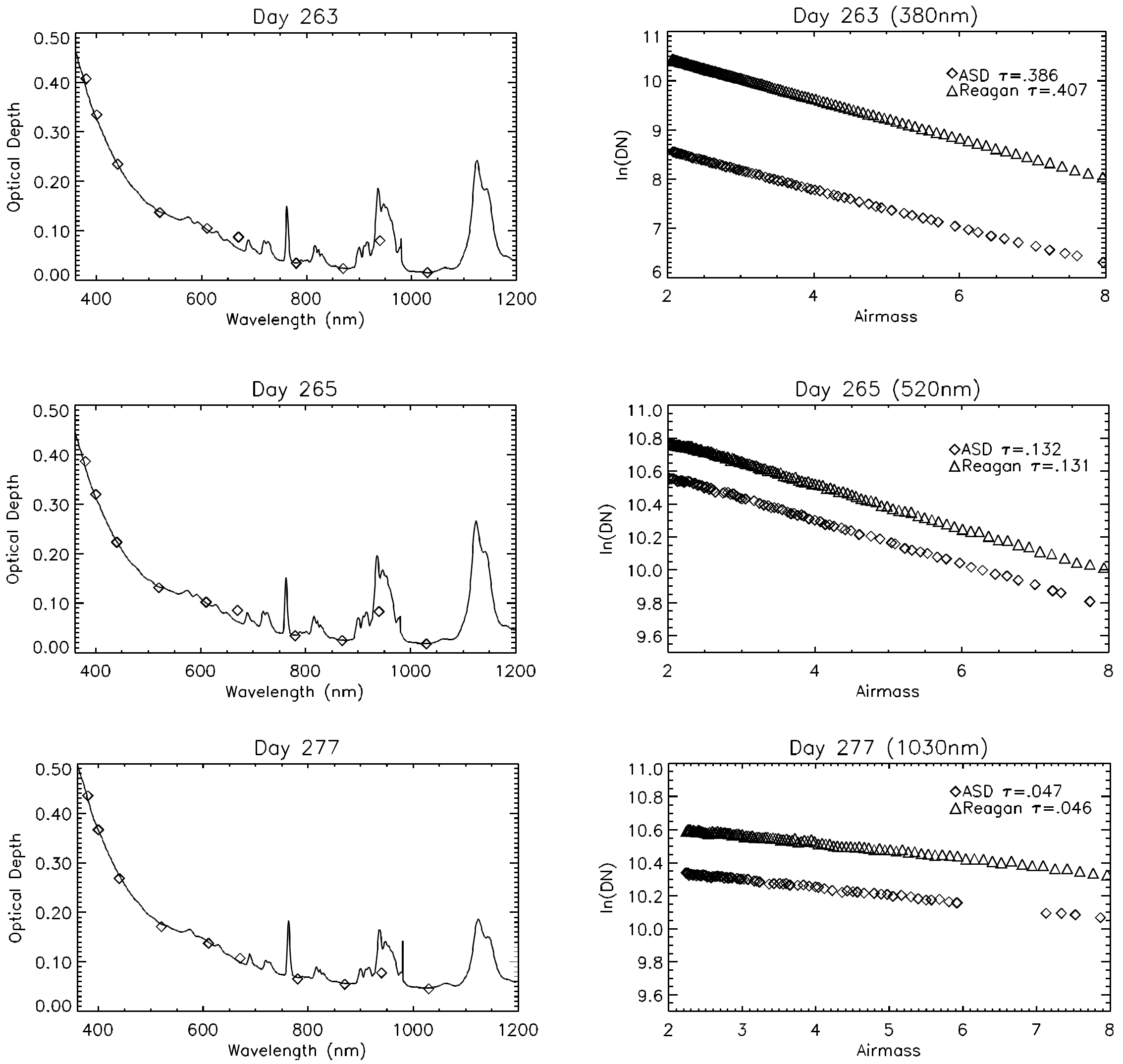

Figure 2. Three side by side experiments for the ASD-FR and Reagan Solar Radiometer. For strong absorbers in the ASD-FR measurement, the optical depths are linear fits to airmass and ln(DN) and thus are not true optical depths.

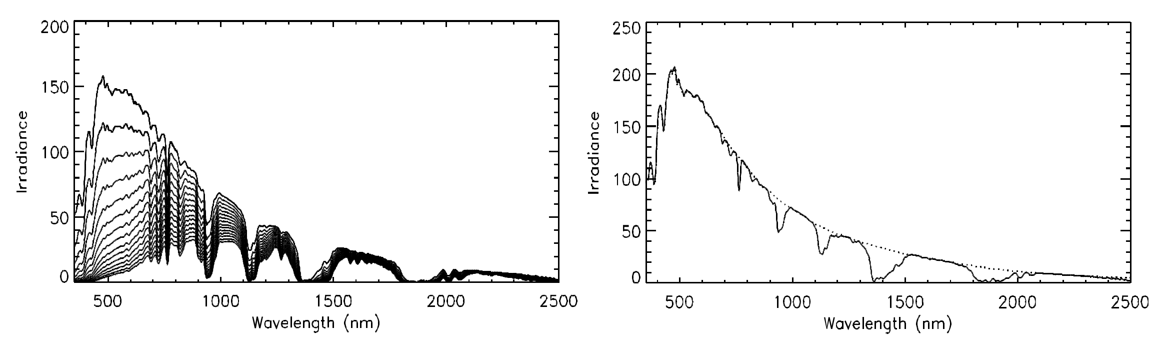

Figure 3. Fifteen MODTRAN modeled irradiances, evenly spaced in airmass are shown on the left. The Langley recreated solar spectrum (solid line) and the input model solar spectrum (dotted line) are shown on the right.

6. Langley Calibration

A series of Langley calibration experiments were undertaken at the Niwot Ridge Mountain Research Station. Niwot Ridge is a high mountain site located approximately twenty miles west of Boulder, Colorado at an elevation of 2.87 km. Fifteen experiments over a month and half yielded eight runs under clear and stable conditions that were considered to be calibration quality. The results from these eight experiments are shown below. Nearly all of the intercepts can be reproduced to 1.5% or better as measured by the percent standard deviation, demonstrating the excellent radiometric stability under field conditions. As expected, the shorter wavelengths have slightly higher uncertainties due to higher optical depths and thus steeper slopes. In the 1000nm to 2000nm wavelength range the agreement is considerably better and is probably a function of the small optical depths and the excellent radiometric stability as shown in the laboratory.

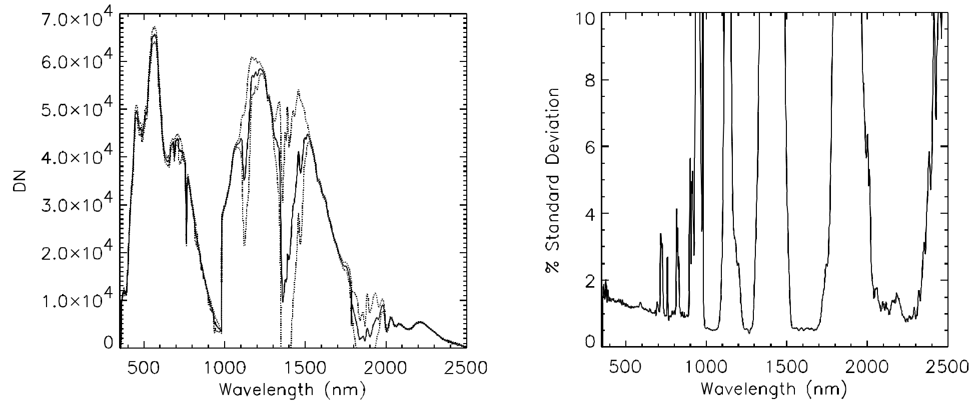

Figure 4. The mean Langley extrapolated DN spectrum (solid line) for eight calibration quality experiments performed at the high altitude Niwot Ridge site are shown on the left. Also plotted on the left are +/- 2 standard deviation spectra (dotted lines). On the right is the percent standard deviation spectrum, the low optical depths (mild slopes) in the 1000nm to 2000nm wavelength range combined with the excellent radiometric stability produce the smallest uncertainties.

7. Calibration in Non-Langley Channels

As shown in the previous analysis, more than 80% of the channels measured by the ASD-FR cannot be calibrated directly with the Langley method. Modifications to the standard Langley fit have been proposed by Reagan for the water vapor band at 940nm to enable calibration at this wavelength (Reagan et al 1992). The modification of standard Langley analysis to each absorber present in the ASD-FR measurement is not an attractive solution to the problem of calibration in non-Langley channels. Instead we propose an alternative method. We rely on NIST traceable standards (bulbs) to only accurately reproduce their spectral shape. The telescope is aligned carefully with a laser to the standard in the laboratory to maximize the input into the integrating sphere. All of the geometrical considerations in a radiometric calibration (e.g. source/receiver distance, telescope aperture size, etc) are grouped into one scaling factor that is independent of wavelength. This scaling factor is determined from the ratio of the Langley determined coefficients to the bulb coefficients in the valid Langley channels. This scaling factor is then applied to the bulb calibration to fill in where Langley is not valid and should closely agree with the coefficients where Langley is valid. Mathematically:

$$\frac{DN}{SolarIrradiance_{Langley}} = \frac{DN}{Irradiance_{Bulb}} \times ScalingFactor$$

The agreement between the bulb-scaled and Langley-derived coefficients are generally very good, with 69% of the channels within +/- 1% of each other and 96% of the channels within +/- 2%. Larger discrepancies tend to occur at the edges of strong absorption features. This is probably due to slight errors in the spectral calibration and can be eliminated by an additional constraint that the valid channel must also be at least one channel away from a non-valid channel.

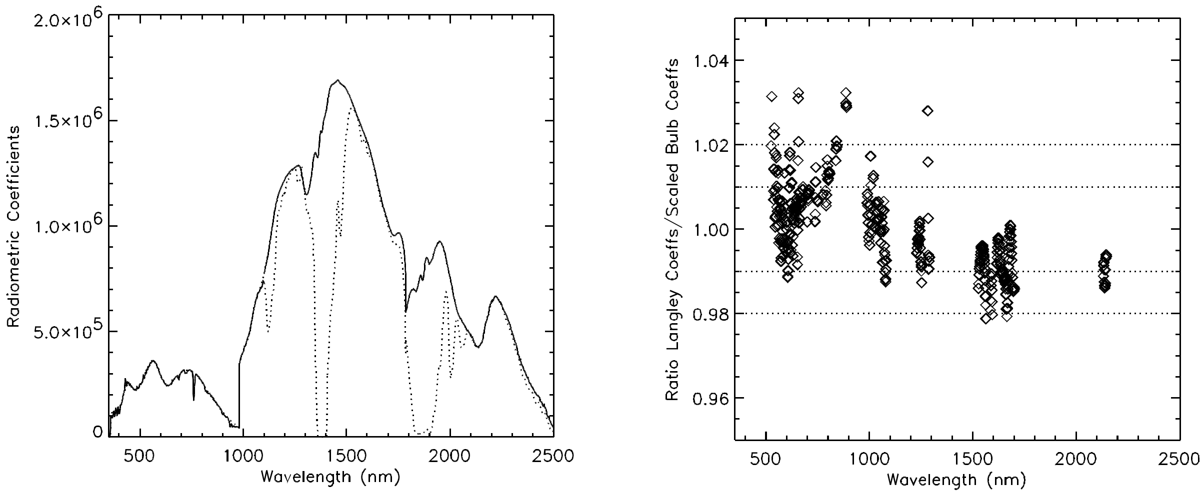

Figure 5. On the left the coefficients for the laboratory calibration is shown after applying the scaling factor (solid line). The coefficients derived from Langley analysis are also shown (dotted line). On the right, the ratio of Langley derived to bulb scaled coefficients are shown for the 379 channels previously determined to be valid Langley channels.

8. Measurements Coincident with AVIRIS

Fortuitously, the AVIRIS instrument was flown over the Table Mountain Observatory during the experiment period as a part of another investigation ongoing at CSES. Surface based irradiance measurements were made throughout the morning and afternoon of the day of the flight September 30, 1999. The measurement closest in time to the AVIRIS overpass was selected and a series of MODTRAN simulations were made to best match the measurement by varying visibility, ozone and water vapor. The ASD-FR measured and MODTRAN-modeled irradiances are plotted in Figure 6 below. The ASD-FR-measured irradiance was divided by the TOA solar spectrum to determine the transmittance and is also plotted in Figure 6. Overall the agreement is excellent, with the differences rarely exceeding 5% outside of regions of strong absorption. The day was dry, the retrieved water vapor amount was less than 1 cm, and very clear with a retrieved visibility of 500km. Differences in the depths of some features may, in part, be attributed to inexact bandpass knowledge for the ASD-FR instrument. Sharp, strong atmospheric absorption features are exquistely sensitive to instrument resolution. Simulations with MODTRAN have shown that a 0.5nm change in FWHM over the oxygen-A band can result in a nearly 10% change irradiance.

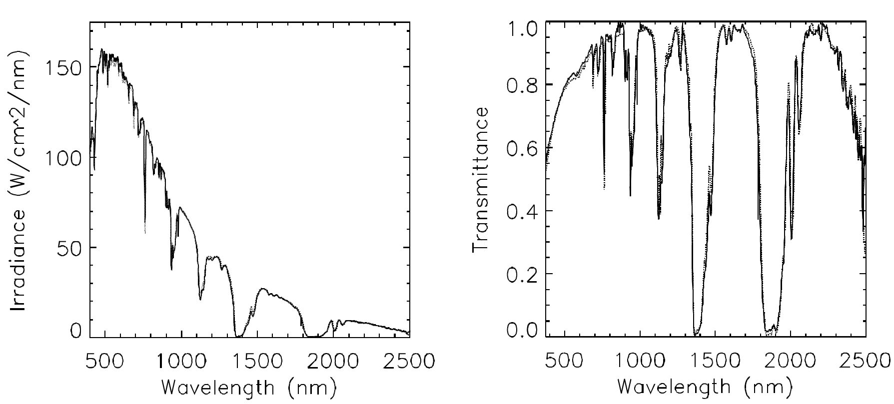

Figure 6. Instantaneous direct solar irradiance at AVIRIS overpass is plotted on the left, the solid line is the ASD-FR measurement and the dotted line is the MODTRAN irradiance after adjusting visibility, ozone and water vapor. The transmittances are shown on the right.

9. Surface Reflectance Retrieval

With MODTRAN parameterized from the inputs to the best fitting irradiance spectrum, we retrieved surface reflectance for several sites within the AVIRIS scene. One example over green vegetation is shown in Figure 7 below. Unfortunately a simultaneous ground reflectance measurement could not be made. The spectrum from Figure 7b is a baseline retrieval, with an unaided estimate of visibility and model defaults. The spectrum 7c is retrieved with parameters determined from the irradiance measurement. The ratio of the two is also shown (7d). Not surprisingly the spectra look quite good, which is generally the case under high visibility and low water vapor amounts-ideal conditions for imaging spectrometry.

In addition to better atmospheric parameterization, it also may be possible to apply a residual spectrum from ratio of the measured to modeled transmittances. Figure 7a is the ratio of measured to modeled transmittances convolved to AVIRIS wavelengths. Figure 7e is the retrieved reflectance with the residual transmission spectrum included and the ratio of the reflectance to the baseline reflectance (7f). The results are mixed. While seemingly improving the reflectance around the 940nm water band, it also introduces a residual oxygen feature and accentuates the errors around the 1140nm water vapor feature. These problems probably arise from using nominal resolutions for the ASD-FR without actually scanning the instrument to determine the exact bandpasses. In addition, the resolutions differences beyond 1000nm between ASD-FR (~11nm) and AVIRIS (~10nm) may make it impossible to apply this technique in these wavelengths.

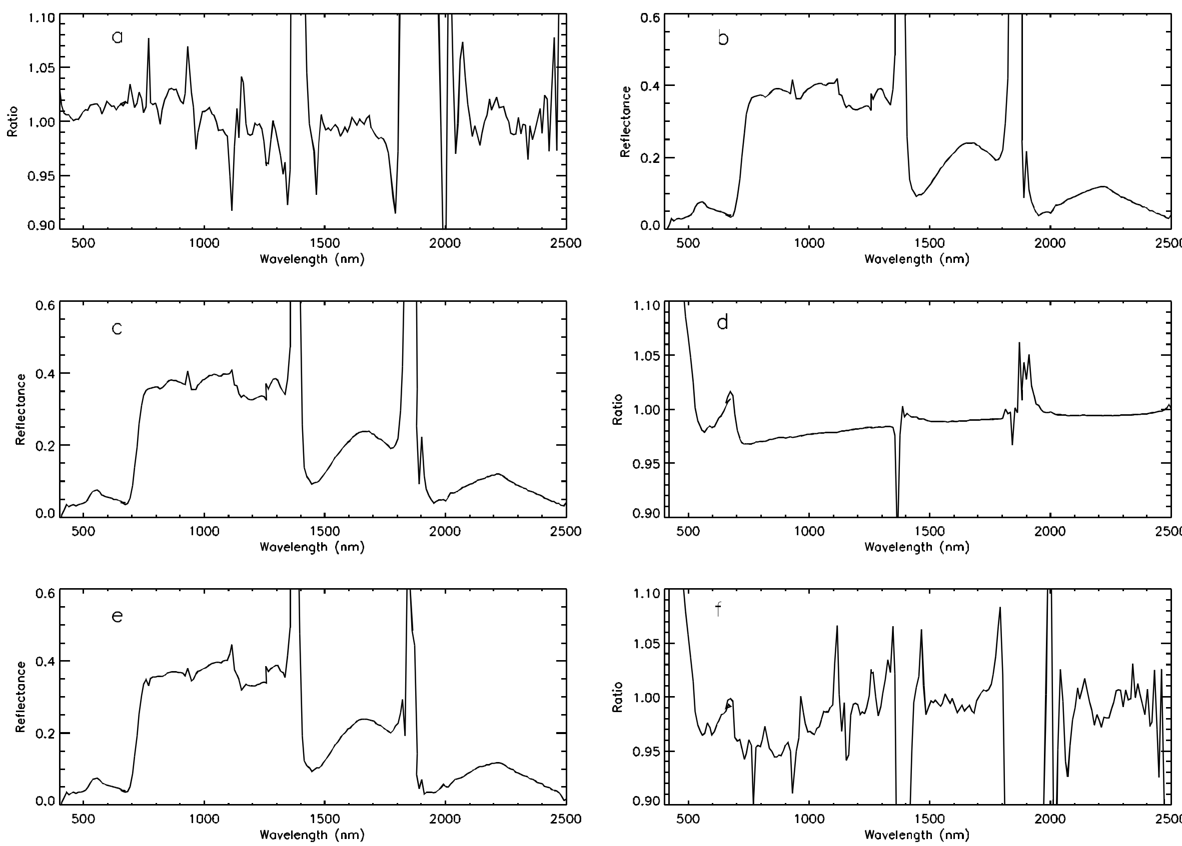

Figure 7. Surface reflectance retrievals for green vegetation. a)ratio spectrum ASD measured transmittance to MODTRAN modeled transmittance, b)baseline retrieval, c)retrieved reflectance with measured parameters, d)ratio of spectra c/b, e)retrieved reflectance with measured parameters and transmission residual adjustment (a), f)ratio of spectra e/b.

10. Conclusions

With recent upgrades to the cooling and dark current to the ASD-FR spectroradiometer can now be used as a hyperspectral solar radiometer with the inclusion of a simple telescope and integrating sphere. A side by side experiment with the Reagan solar radiometer has shown excellent agreement between the two instruments in overlapping channels. The system can be calibrated to published TOA solar spectra for comparisons with radiative transfer codes both in valid Langley channels as well as regions of strong absorption. A stable, well-calibrated instrument should allow for better parameterization of the atmosphere during data acquisition. Exact bandpasses must be determined for the ASD-FR before any conclusions can be made about the viability of a residual transmission correction. In addition, measurements must be made under a variety of water vapor and scattering conditions to determine the utility of this technique. These measurements have a wide variety of applications both in remote sensing and atmospheric science.

11. Acknowledgements

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