

IMPROVED ATMOSPHERIC CORRECTION FOR AVIRIS SPECTRA FROM INLAND WATERS

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As part of an ongoing investigation of primary productivity in Mono Lake, a series of surveys were conducted at the lake coincident with AVIRIS acquisitions. These included sampling and spectroradiometric measurements with locations precisely georeferenced to AVIRIS pixel coordinates. Spectra were extracted from the AVIRIS images for the purpose of deriving predictive equations for calculation of chlorophyll based on the atmospherically-corrected remote sensing reflectance.

Remote sensing reflectance, R_{rs} , is defined as the ratio of upwelling radiance to incident downwelling irradiance. It can be retrieved from the radiance AVIRIS measures by simulating the solar and atmospheric contributions with a radiative transfer model. We used the version of modtran3 partly developed at JPL for this purpose. However, a modtran simulation has not been sufficient for most of our datasets. We found agreement with in situ spectra much improved by including a ratio of radiances over a land site, in situ radiance divided by AVIRIS radiance, in our calculation of R_{rs} .

The accuracy of the atmospheric correction was evaluated by (1) comparison of in situ spectra to retrieved AVIRIS R_{rs} , (2) comparison of spectra from land, (3) matching in situ skylight spectra to modtran output skylight, and (4) matching gray card reflectance to modtran modeled downwelling irradiance. Precision was assessed by comparison of AVIRIS spectra from the same location on the lake from adjacent overpasses.

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1. INTRODUCTION

Remote sensing reflectance (Rrs) cannot be measured directly. Comparison of Rrs calculated from field measurements to Rrs calculated from AVIRIS spectra and the atmospheric radiative transfer model modtran provides a measure of the accuracy of our method. That and other comparisons are presented here as a validation of a method of retrieving Rrs from inland waters from AVIRIS radiance. The method of collecting field measurements for Rrs is described in Hamilton, 1993. Retrieval of Rrs from AVIRIS using modtran was developed from Carder, 1993. AVIRIS radiance is reduced by the path radiance modeled by modtran and divided by one-way transmission. Skylight, modeled by modtran, specularly reflected from the lake surface, is then subtracted from this radiance, leaving only that radiance which has come from under water. This water-leaving radiance is then normalized by the downwelling irradiance incident at the surface as modeled by modtran. Separate executions of modtran are made, in different modes, with the appropriate viewing geometry, to calculate the parameters of this equation:

$$Rrs = [(L_{AVIRIS} - L_{path}) / T_{atm} - L_{sky} * \rho_{water}] / E_d$$

where L_{AVIRIS} is radiance measured by AVIRIS,

L_{path} is path radiance, indirect solar radiance at the view angle from nadir, at AVIRIS,

T_{atm} is atmospheric transmission, one-way,

L_{sky} is skylight, indirect solar radiance at the view angle from zenith, at the surface,

ρ_{water} is the Fresnel reflectance coefficient of water,

and E_d is the downwelling solar irradiance incident at the lake surface.

Our improved retrieval of Rrs has allowed us to fit a single curve to a set of 134 pairs of AVIRIS Rrs and measured chlorophyll gathered on eight experiments at Mono Lake. Previously, spectra from different surveys varied more due to lingering atmospheric effects and/or radiometric calibration imprecision than they varied due to chlorophyll.

2.0 USE OF MODTRAN

2.1 Modtran Model Inputs

The modtran version we used was shared with us by Robert Green (JPL); partly developed at JPL, an intermediate version between version 3 and 3.5, it is of circa 1993 vintage. It uses an updated solar spectrum and allows the user to specify gas amounts. In all cases we used 0.55 of nominal water vapor and 1.06 of nominal CO₂ specified in modtran. The effect of input H₂O vapor amount is limited to the water vapor absorption bands. This modtran version allows the surface albedo spectrum to be read from a file rather than using a scalar constant. The inclusion of 8-stream discrete ordinate scattering improved the modtran outputs' match to our measurements. For all cases the mid-latitude, rural model was used.

Some modtran inputs are less precise than the date, hour, viewing geometry and geographic location. These imprecisely defined inputs are used to optimize the match between modtran-retrieved Rrs and Rrs calculated from ground-based measurements. Of these, horizontal visibility has the greatest effect. Estimates of actual horizontal visibility at Mono Lake during AVIRIS experiments ranged from 100 to 200 km. The one date for which we have optical depths calculated from sun photometer measurements had a calculated visibility of 440 km. Modtran output is decreasingly sensitive to visibility as visibility increases.

2.2 View Angle Sensitivity

Path radiance, the largest part of the radiance measured at 20 km altitude over water, varies with view angle, as do T_{atm} and L_{sky} . The view angle of each survey station on the lake was calculated from its cross-track pixel location. Nominal values for an ER-2 altitude of 20 km and a scene total width of 11 km were assumed, understanding that any variation is a similar triangle to this geometry. A side scan of 16 degrees was assumed for the edges of the image; zero roll was assumed. Based on the regularity of the shoreline topography, we deduced that usually the roll was negligible.

Interpolating the modtran parameters L_{path} , T_{atm} , and L_{sky} to each station's specific view angle brought the same stations' spectra extracted from duplicate AVIRIS coverage into closer agreement. The effect of side-scan angle on the modtran parameters in the Rrs equation removed the largest part of the discrepancy between Rrs spectra of the same station in subsequent runs. All field measurements were done at zenith or nadir; Rrs is independent of view angle even though it is calculated from parameters dependent on view angle.

Modtran outputs for nadir and 15 degrees off nadir were used to linearly interpolate more precise L_{path} , T_{atm} and L_{sky} for each survey station. A good approximation is that L_{path} , L_{sky} and T_{atm} vary linearly with view angle. View azimuth was always 90 degrees from the solar plane because we requested the ER-2 fly directly at or away from the sun, so as to avoid sun glint. The left and right sides of the viewing geometry were treated symmetrically. Modtran was run with view azimuth to the east of the flight track.

3.0 VALIDATION

3.1 Skylight Comparison

Our intention was to choose a visibility for which the measured L_{sky} most closely matched the modtran output L_{sky} . Every field survey included sky spectra at zenith. However, the field measurements of skylight were variable, more so than changes in visibility. The modtran L_{sky} and that measured in the field are compared in Figure 1 for 7Oct92, but the choice of visibility is not obvious because the comparison is complicated by the different slope of the modtran modeled L_{sky} and field measured skylight spectra. Modtran models the skylight as more blue than was actually measured; the modtran skylight exceeds that measured in the blue end but is less than that measured in the red end. The modtran L_{sky} is theoretical, and so has an infinitesimal fov. The fiber optic tip of the field spectrometer has a full width field of view (fov) of 22 degrees.

3.2 Downwelling Irradiance Comparison

Figure 2 shows that the downwelling irradiance modeled by modtran is less blue than that measured in the field, by either the gray card or the remote-cosine-reflector. The modtran modeled E_d is used in the denominator of the equation to retrieve Rrs from AVIRIS radiance. Modtran output E_d differs from that measured off the gray card by approximately a linear factor increasing from zero at 400 nm to 25 $\mu W/nm/cm^2$ at 800 nm. The effect of this difference in the denominator is to calculate a Rrs increasingly too low toward longer wavelengths. However, that is opposite to observed discrepancy between field measured and AVIRIS Rrs spectra.

3.3 Optical Depth Comparison

Atmospheric optical depth is the extinction integrated along the path. It varies with path length and concentration of molecules and aerosols. An atmosphere is well described by its optical depth. Optical depth may be partitioned into its separate contributors, but in this example we consider the total. A Reagan sun photometer was used to measure the intensity of direct solar radiance in nine channels as a function of time-of-day. From the curve of changing path length to the sun through the atmosphere, called a Langly plot, the optical depths were deduced. We collected sun photometer data successfully on most of our AVIRIS experiments but only one data set was reduced. We have optical depths for the 21Sep93 AVIRIS experiment.

Modtran calculates total optical depth, a unitless quantity. We used the optical depth from a modtran case for skylight at zenith and at 15 degrees off zenith for comparison to the sun photometer-measured optical depths. Figure 3 shows the modtran output as dots (so finely resolved that they appear almost continuous) and the sun

photometer channels' optical depths as diamonds. Figure 3 shows that optical depth is sensitive to the model used in modtran, and that the mid-latitude winter model is a better match for 21Sep93 than the mid-latitude summer.

3.4 Pumice Flats Comparison

Our land calibration site just 5 km south of Mono Lake is a 2 km wide, flat area covered with white pumice gravel named Pumice Flats. To improve the radiometric calibration (the factor of radiance over DN, where DN is digital number), the field spectra at Pumice Flats are ratioed to the spectra extracted from AVIRIS cubes at Pumice Flats. The field spectra are measured as DN over the pumice gravel and DN over the gray card to calculate reflectance, R_{PF} . This is radiance reflectance, not R_{rs} . To obtain the equivalent radiance that would be seen at 20 km altitude, the modtran outputs L_{path} , T_{atm} , and E_d are used.

$$L_{PF} = R_{PF} * (E_d/\pi) / T_{atm} + L_{path}$$

In calculating a radiance-at-sensor (L_{PF}) from the field measured reflectance (R_{PF}) we used modtran output irradiance rather than radiance. This method may produce a better L_{PF} . The gray card is Lambertian. The denominator in the field measured reflectance is E_d/π . The gravel in Pumice Flats is oriented at all angles so, although specular on each tiny surface, as an aggregate it will be somewhere between specular and Lambertian.

The AVIRIS radiance spectrum of Pumice Flats is the average of several hundred pixels. An average of three years' Pumice Flats field reflectance spectra is used in the numerator of all dates' radiance correction ratio. The spectra are resampled to the AVIRIS band center wavelengths of the year being processed. Radiance correction ratios calculated for six dates are graphed in Figure 4.

The total radiance AVIRIS measures at 20 km altitude is nearly all path radiance. If modtran has accurately modeled the path radiance, it should be less than the AVIRIS radiance. All variables in the equation below are positive.

$$L_{AVIRIS} = L_{path} + L_{sky} * \rho_{water} + L_{water}$$

When the AVIRIS radiance over the water is less than the modtran output path radiance, we know either the path radiance is incorrectly modeled or the AVIRIS radiance calibration is wrong. If the ratio from Pumice Flats brings the AVIRIS radiance above the path radiance, it could be correctly adjusting the radiometric calibration or mitigating inaccuracy in the modtran outputs.

If a lake spectrum was used instead of the Pumice Flats spectrum to create the radiometric calibration correction ratio, then that AVIRIS spectrum would be forced to agree with the field spectrum. This may be useful for making a chlorophyll map of one date, but this is counter to the purpose of finding the best predictive algorithm for multiple dates. The Pumice Flats reflectance has been found to be consistent over time-of-day and season.

3.5 Comparison of Same Station in Subsequent Overpasses

Two to three overpasses are required to cover Mono Lake, our ground control points on shore and land calibration site. On some dates these AVIRIS runs overlap, providing duplicated coverage of our stations on the lake. Comparison of spectra from the same station in subsequent overpasses has unexplained variability. AVIRIS spectra extracted as the average of a 10x10 bin of pixels centered on a station location (accurate to 2 to 4 pixels by georeferencing) should have near identical shape and magnitude. Their only differences are the 10 to 20 minute delay and resulting small sun angle change and drift of the lake water. A current on a calm day of 5 cm/s causes a drift of only 30 to 60 meters, which is only a fraction of a 200 m wide bin.

The small change in solar angle does affect modtran output measureably and so the time-of-day was input specific to each overpass. The time-of-day used was that where the ER-2 would be over the center of the stations covered in that overpass. Each scene of 512 lines takes 42 seconds to fly, so the ER-2 is over the lake for about 84 seconds on each pass.

A larger discrepancy between runs occurs when the ER-2 flies in the opposite direction (N->S then S->N). If there is stratospheric wind then the ER-2 must fly at a different altitude. Pixel area increases with altitude but the instantaneous field-of-view (ifov) remains constant. Because the stratosphere is so optically thin, a 0.5 km change

in ER-2 altitude does not affect the modtran outputs enough to explain the change in calculated Rrs. We have not determined the cause of the difference in brightness in overpasses flown from opposite directions.

3.6 Georeferencing Precision

The location of the stations on the lake was performed with care and with many more ground control points (GCP) than a second order transform requires. A set of 204 GCPs in the six topographic maps containing Mono Lake were measured which allowed ill-fit GCPs to be discarded until a rms error of less than 4 pixels was achieved in most scenes. A 10x10 bin of pixels was used to extract one average radiance spectrum at each survey station.

3.7 Rrs from AVIRIS Compared to Rrs from field spectra

In Figure 5 the Rrs calculated from field spectra and from AVIRIS spectra are overlaid for comparison on two dates. Eight dates were examined. The AVIRIS Rrs deviate most from the field spectra at the blue end, at wavelengths shorter than 440 nm, for most of these dates. At 490 nm the spectra are closer; and at 555 nm the field spectra and AVIRIS Rrs agree well; 17Aug94 is a counter-example of this. We attribute the differences mainly to an imperfect atmospheric correction but also partly to radiometric calibration of the blue wavelengths. The radiance ratio from Pumice Flats should compensate for most errors in the radiometric calibration. Because the ratio denominator was calculated with the same modtran outputs as were used to retrieve Rrs, the ratio partially compensates for those outputs' inaccuracy.

The field spectra within a survey do vary in amplitude, with close to identical shape. This is most evident in 20May94 spectra. This same phenomenon appears in AVIRIS spectra. This may be attributed to small fractions of a pixel (or fov of the field spectrometer) containing foam or flecks of sun glint from ripples. Only in the AVIRIS spectra can this raised amplitude be explained by stratospheric aerosols. In that case the Rrs(800nm) may be subtracted as a constant from the entire spectrum as a first approximation. This was done to the 1992 AVIRIS spectra.

4. OTHER SOURCES OF VARIABILITY AND ERROR

4.1 Coherent Noise

Two types of noise appear in AVIRIS images besides the random speckle caused by very low signal being digitized: diagonal stripes and horizontal swaths. The diagonal stripes became less a problem in each AVIRIS season as the instrument shielding and dynamic range improved. In years prior to 1995, when the roll-correction was done, the de-stripping algorithms were thwarted because the images do not have the original time sequence in the signal. A simple boxcar smooth worsens the stripes unless the box is much larger than the stripes.

The second noise type, appearing as horizontal swaths, is caused by variation in dark current (DC). This effect was removed by averaging all lines of dark current in each scene before subtracting from raw DN. 1996 data are the first for which the DC vary less than one DN across a scene.

4.2 Shoreline Ghosts - 1996 Forward-looking Window Beam Split

The 1996 data had a unique error source. An internal refraction in the window was blamed for a split beam, resulting in the image 250 lines forward of nadir appearing also at nadir as a small fraction of the main beam's amplitude. This appeared in the image as a faint overlay of the same image, offset by 250 lines. Where the shore was many times brighter than the lake radiance, this ghost image caused a measurable error. Where stations were more than 250 lines before the shore, the error was not measurable. We detected this phenomenon in the 2Apr96 Mono Lake AVIRIS images, when the shore was exceptionally bright due to new snowfall.

5. SUMMARY

Comparisons between AVIRIS and field spectra have assessed our method of atmospheric correction. The radiance correction ratio calculated from AVIRIS radiance over a land calibration target significantly improved the agreement between field measured and AVIRIS Rrs for all but one survey. By varying modtran inputs to optimize the fit between AVIRIS and field spectra we have improved the consistency of our Rrs spectra of Mono Lake collected in eight surveys.

6. ACKNOWLEDGMENTS

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The AVIRIS field experiments at Mono Lake were a success due to team effort involving M. Embry, G. Dana, D. Heil and B. Jellison from 1992 through 1996. Sun photometer data was reduced at JPL by J. van den Bosch. The UCSB Maps and Imagery Laboratory provided access to ERDAS georeferencing software, training, and advice. R. Green provided the input/output shell for modtran and valuable discussions. Modtran was run on a DEC alpha at JPL. D. Roberts reviewed the methods and provided insight on modtran use.

7. REFERENCES

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Hamilton, M.K., C.O. Davis, W.J. Rhea, S.H. Pilorz, and K.L. Carder, "Estimating chlorophyll content and bathymetry of Lake Tahoe using AVIRIS data." *Remote Sens. Environ.* 44 (1993): 217-230.

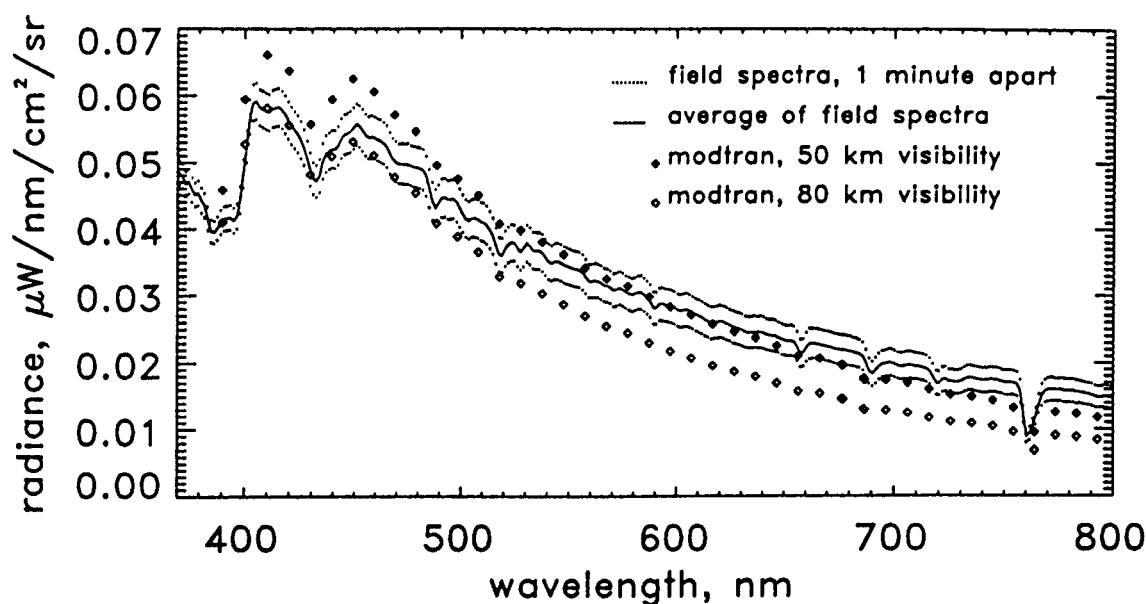


Figure 1. Measured skylight validates the modtran inputs.

The field measurement of skylight at zenith coincident with AVIRIS overflight can be used to select the modtran input visibility and to test the accuracy of the modtran model. The two field spectra, measured with the unbaffled fiber optic tip of a PS-II spectroradiometer (Analytical Spectral Devices) are plotted as one dot per 1.4 nm spaced waveband. The bands are so close that the spectrum shows fine atmospheric absorptions. Two skylight measurements are shown here, measured one minute apart. Their average is the solid line. The modtran simulated skylight at zenith is resampled to AVIRIS wavebands and plotted with a diamond at each band center. The solid diamond spectrum is from input visibility 50 km and the open diamonds from 80 km.

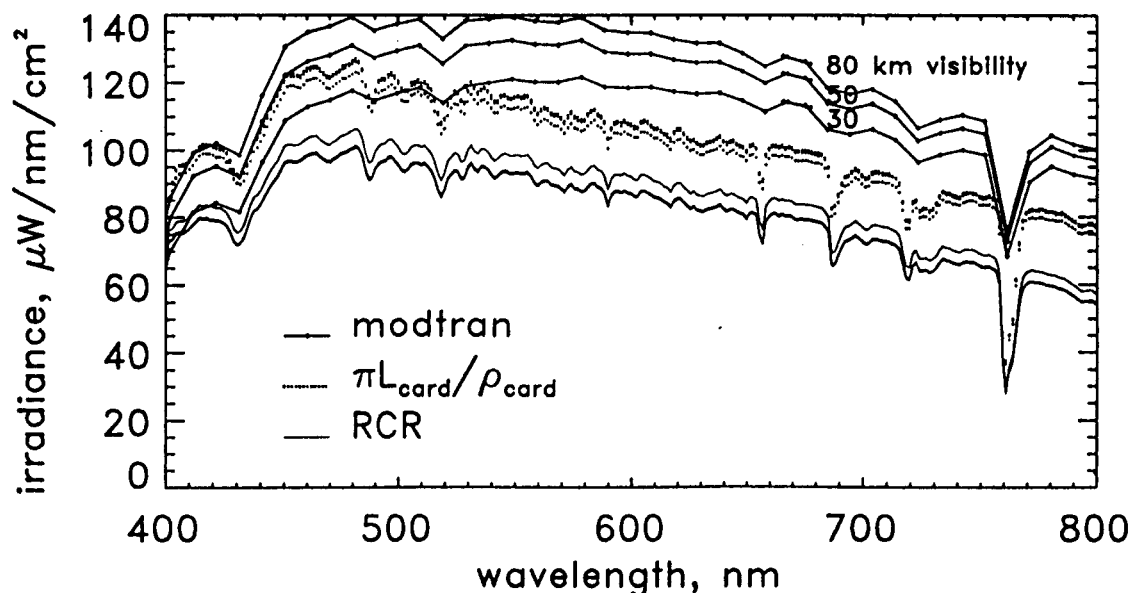


Figure 2. Modtran E_d compared to two field measurements of E_d .

Modtran models downwelling irradiance incident above the lake surface as brighter and less blue than we measured on the lake. E_d was measured directly using the remote cosine receptor (RCR) at the moment of AVIRIS overflight; three trials are graphed, solid curve. R_{rs} is calculated using the approximation of $\pi L_{card}/\rho_{card}$; radiance reflected off the gray card moments after overflight (dotted spectra) are brighter than measured with the RCR.

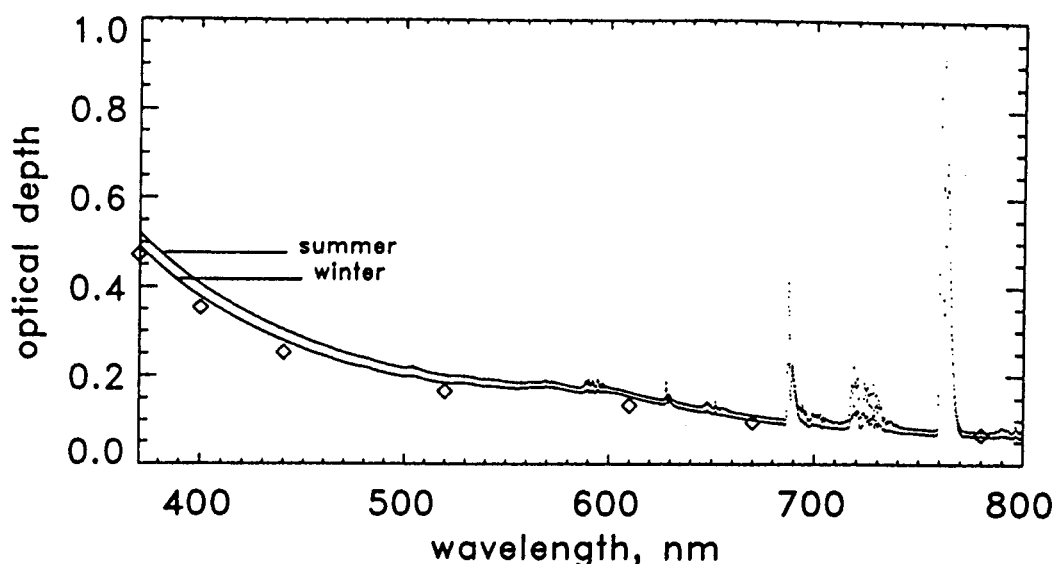


Figure 3. Modeled and measured atmospheric optical depth.

The optical depth output from the modtran model is graphed at high spectral resolution; inputs are specific to the 21Sep93 AVIRIS overflight conditions; summer and winter cases are compared. Optical depths calculated from sun photometer measurements on that day are graphed as diamonds. This comparison indicates a winter tropospheric temperature profile is appropriate.

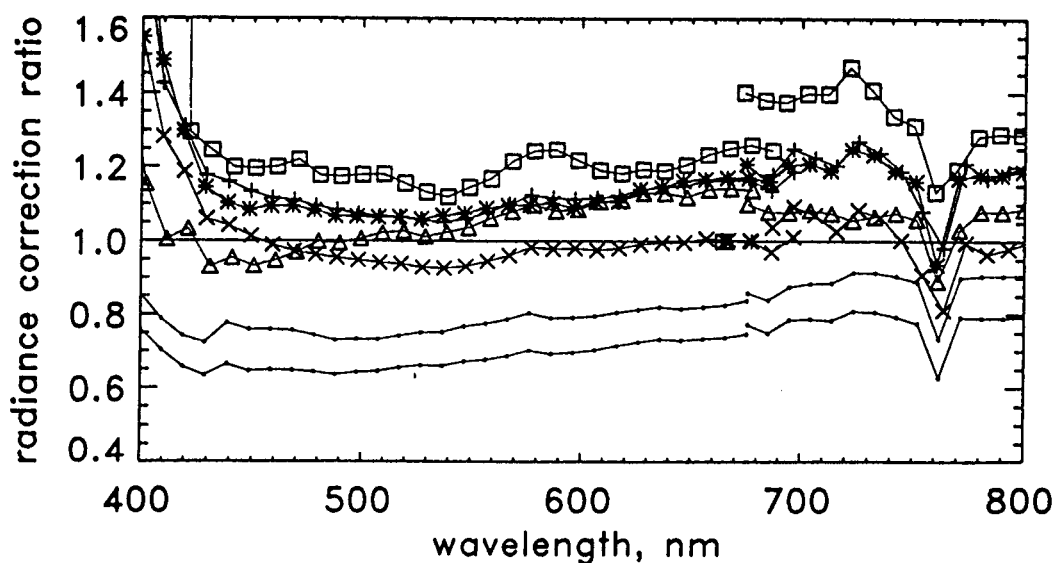


Figure 4. Radiance correction ratios for six AVIRIS dates.

For six overflights of Pumice Flats the ratio of field measured reflectance propagated to a radiance at 20 km over the AVIRIS radiance is graphed. For the spectral region of interest, about 440 nm to 710 nm for the purpose of predicting chlorophyll, these correction ratios vary from 0.9 to 1.3, with the exception of the 2Apr96 flight. On 2Apr96 Pumice Flats is covered in two overpasses; a correction ratio is calculated for each. These ratios, from 0.6 to 0.9, do not improve the match of AVIRIS Rrs to field measured Rrs. We speculate this is because for this date only the on-board calibration was already incorporated in the AVIRIS radiance. For all other dates, these correction ratios do improve the agreement between field measured Rrs and AVIRIS Rrs.

Plotting symbols:

• 2Apr96
* 21Sep93

□ 10Oct95
+ 7Oct92

△ 17Aug94
x 1Sep92

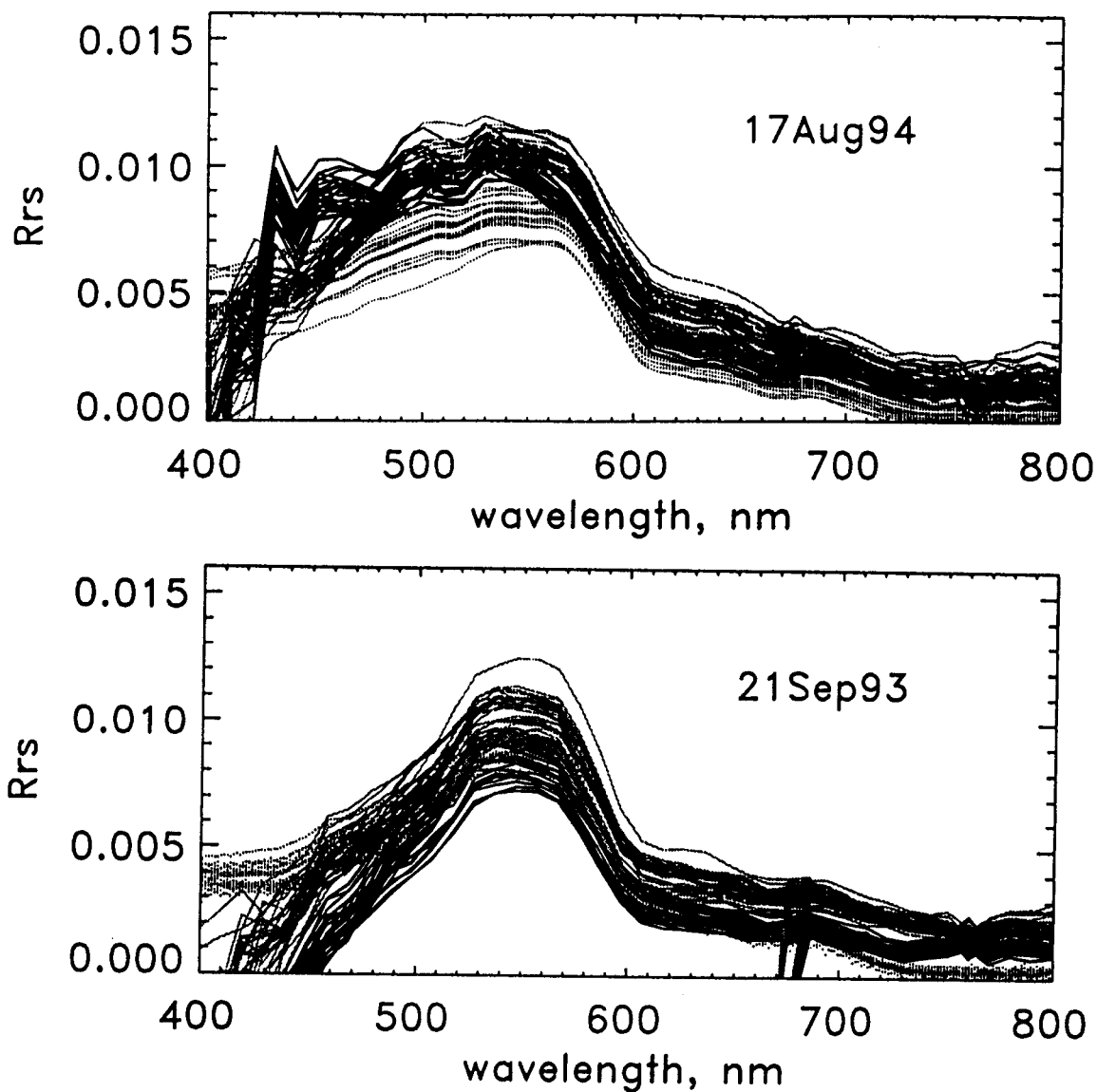


Figure 5. AVIRIS Rrs compared to field measured Rrs.

Rrs calculated from field spectra and from AVIRIS spectra are overlaid for comparison, separately for each of two dates. An 80 km visibility was input to modtran for both Rrs shown in this figure. The dotted curves are the field spectra, one dot per band. The solid black curves are the AVIRIS Rrs spectra without using the radiance ratio from Pumice Flats and the gray curves include that ratio in the Rrs calculation. The gray curves partially obscure the black curves and either solid curves obscure the dotted curves.

For the 17Aug94 AVIRIS spectra the radiance correction ratio smoothes the jags in the wavelengths shorter than 550 nm.

For the 21Sep93 the radiance correction ratio raises the AVIRIS Rrs. Even with the ratio applied, AVIRIS Rrs are negative below 440 nm. With ratio, AVIRIS is a better match to the field spectra up to 550 nm but at longer wavelengths the uncorrected spectra match more closely.