Measuring the Spectral Expression of Carbon Dioxide in the Solar Reflected Spectrum with AVIRIS

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INTRODUCTION

Carbon dioxide is a low-concentration, but important, component of the Earth's atmosphere. This gas absorbs electromagnetic radiation (EMR) in several regions of the spectrum. Absorption of energy by carbon dioxide adds heat to the atmosphere. In the world today, the burning of fossil fuels and other anthropogenic processes adds carbon dioxide to the atmosphere. Other natural processes in the Earth's system both add and remove carbon dioxide. Overall, measurements of atmospheric carbon dioxide at selected sites around the globe show an increased carbon dioxide concentration in the atmosphere. Figure 1 shows the measured carbon dioxide from Mauna Loa, Hawaii, from 1958 to 2000. Overall, the concentration has increased from 315 to 365 ppm at this site over this period. (There is also a yearly cycle to the concentration that is timed with and hypothesized to be related to the vegetation growing season in the Northern Hemisphere.) The overall expected effect of this increase of atmospheric carbon dioxide is trapping of heat in the atmosphere and global warming. While this overall relationship between carbon dioxide and global warming seems straightforward (IPCC, 1996), many of the specific details relating to regional and local sources and sinks and gradients of carbon dioxide are not well understood. A remote sensing capability to measure carbon dioxide could provide important inputs for scientific research to better understand the distribution and change in atmospheric carbon dioxide at detailed spatial and temporal levels.

In pursuit of this remote sensing of carbon dioxide objective, this paper analyzes the expression of carbon dioxide in the spectral range measured by the Airborne Visible/Infrared Imagery Spectrometer (AVIRIS) (Green et al., 1998). Based on these analyses, a spectral-fitting algorithm that uses AVIRIS measured spectra and MODTRAN radiative-transfer code (Berk et al., 1989; Anderson et al., 1995, 2000) modeled spectra to derive total column carbon dioxide abundance has been developed. This algorithm has been applied to an AVIRIS data set acquired over Pasadena, California, in 1999 and a data set acquired over the Pacific Ocean near Hawaii in 2000 with promising results. This is ongoing research; the current initial analyses, measurements, and results are reported in this paper.
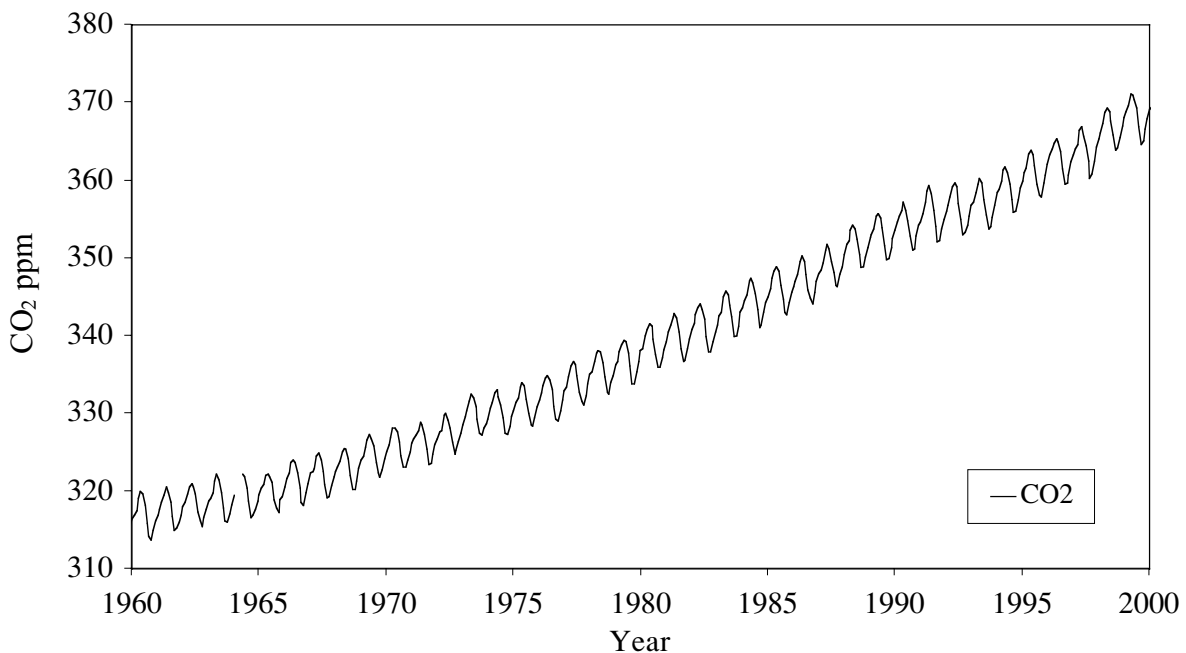
Figure 1. Plot of measured carbon dioxide concentration over time from Mauna Loa (Keeling and Whorf, 2001).

EXPRESSION OF CARBON DIOXIDE IN THE AVIRIS SPECTRUM

AVIRIS measures the upwelling spectral radiance from 370 to 2500 nm at nominally 10 nm sampling. From the ER-2 aircraft platform at 20 km altitude, an AVIRIS spectrum is measured for each 20-by-20 m area across an image approximately 11 km wide and up to 800 km in length. The spectra are spectral, radiometrically and spatially calibrated (Chrien et al., 1990, 1995, 1996, 2000). Figure 2 shows the AVIRIS spectral range and a transmittance spectrum of the terrestrial atmosphere. The effects of aerosols and molecular scattering (as well as the absorption of water vapor, oxygen, methane, ozone, and carbon dioxide) are present in each AVIRIS spectrum. In this portion of the spectrum, water vapor is the dominant absorber, as indicated in Figure 3 that shows a transmittance spectrum of the atmosphere with and without water vapor in the atmosphere. In the AVIRIS spectral range, the principal carbon dioxide absorption bands occur in the 1600 nm and 2000 nm spectral regions. Figure 4 shows the expression of these carbon dioxide absorption bands in an AVIRIS spectrum measured over an area of Pasadena, California on June 22, 1999. In addition to the carbon dioxide features, the AVIRIS spectrum contains the integrated effects of the solar irradiance source, two-way transmittance, and scattering of the complete atmosphere, as well as the reflectance of the surface. To model these effects in measured AVIRIS spectra, a radiative-transfer code is used. The MODTRAN radiative transfer code is one such model. Figure 5 shows a MODTRAN predicted spectrum at high spectral resolution and convolved to AVIRIS spectral resolution. This modeled spectrum accounts for the source, atmosphere, surface, and geometry of the modeled observation.
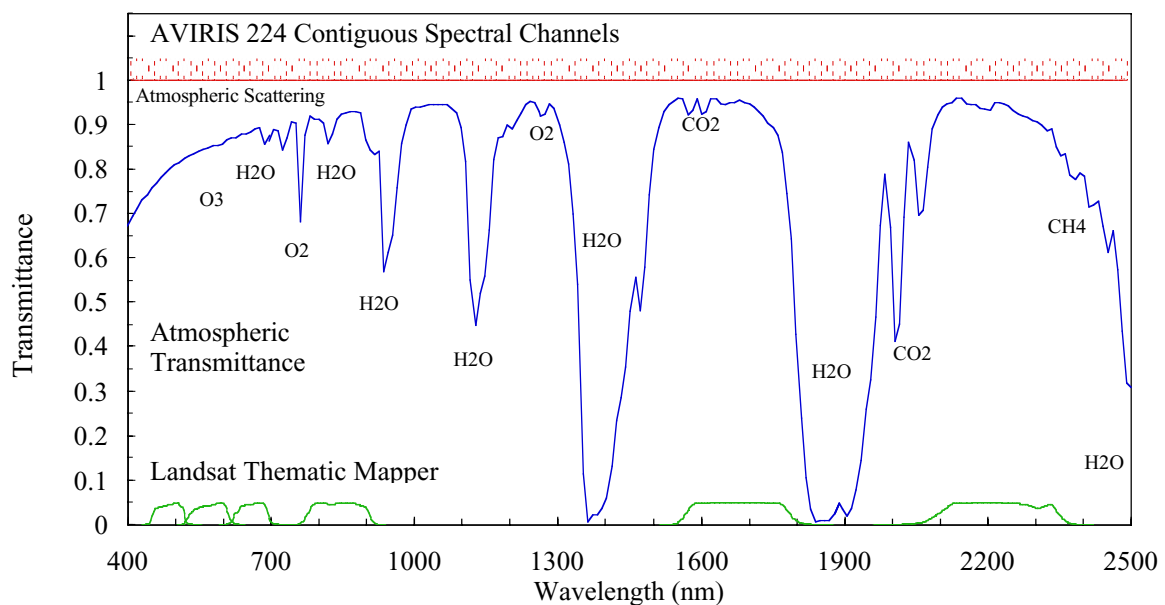
Figure 2. AVIRIS spectral coverage and a transmittance spectrum of the atmosphere. Also shown are the Landsat Thematic Mapper multi-spectral bands.
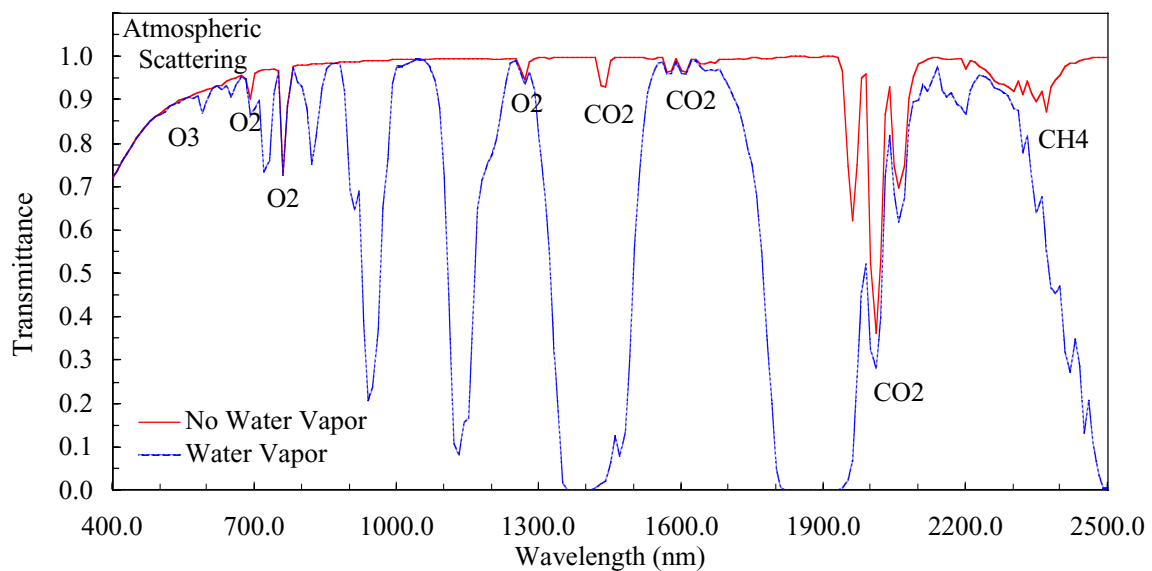

Figure 3. A transmittance spectrum of the atmosphere with and without water vapor convolved to AVIRIS spectral resolution.
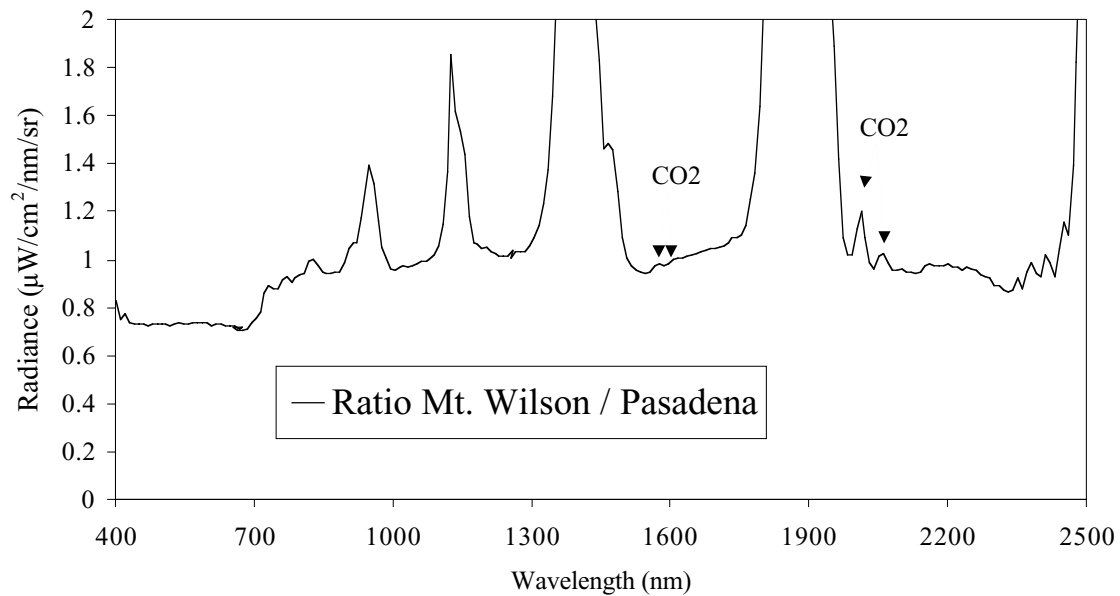
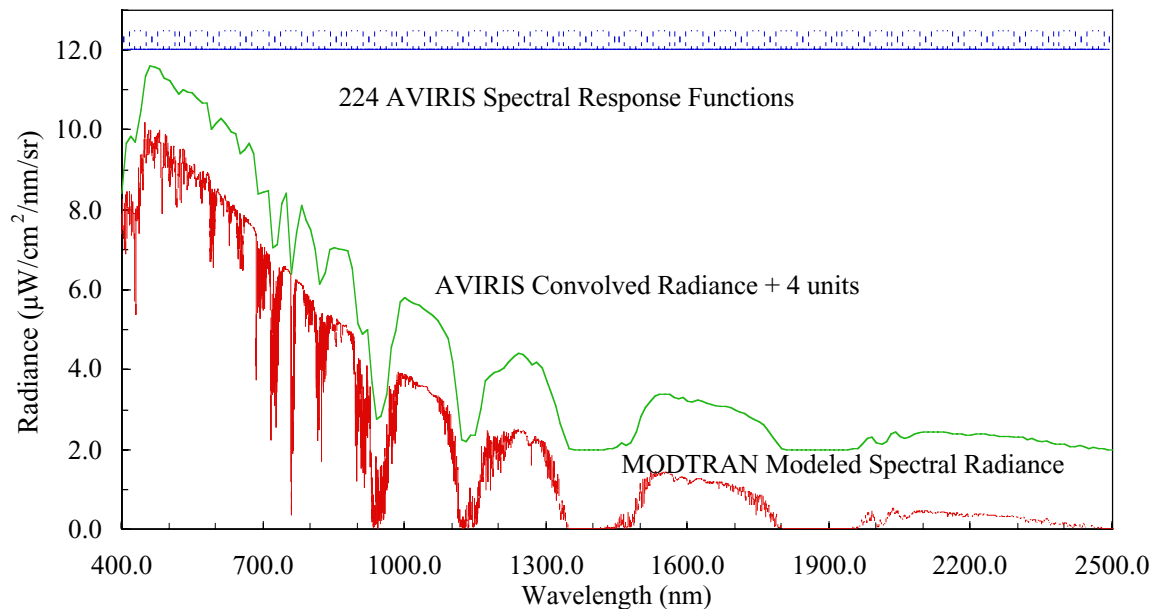Figure 4. AVIRIS calibrated radiance spectrum showing the expression of the absorption of carbon dioxide.

Figure 5. A radiative transfer code modeled spectrum at nominal MODTRAN resolution and convolved to AVIRIS spectral resolution.

CARBON DIOXIDE OVER LAND

To explore the potential for AVIRIS to measure changes in carbon dioxide, an AVIRIS data set acquired over Pasadena, California was identified for analysis. This data set contains the lower elevation areas of Pasadena and the higher elevation areas of the San Gabriel Mountains. Figure 6 show a single-band image of this data set with Pasadena in the center and the San Gabriel Mountains to the left. The 20-by-

20 m AVIRIS data were averaged to 80-by-80 m spatial resolution to improve the data signal-to-noise ratio. From the spatially averaged data set, spectra from the Pasadena city area at an elevation of 350 meters as well as from the Mt. Wilson summit area at an elevation of 1742 meters were extracted. Both spectra were extracted from bright areas with low amounts of vegetation. These spectra are shown in Figure 7. From a path-length perspective, the expressed absorption of carbon dioxide should be greater for the lower-elevation Pasadena spectrum than for the higher elevation Mt. Wilson spectrum. The path downward from the top of the atmosphere to the reflecting surface in Pasadena and upward to the AVIRIS sensor is longer than the corresponding path for the Mount Wilson radiance spectrum. There should be less absorption by carbon dioxide in the shorter Mount Wilson path spectrum. A simple ratio of the Mt. Wilson spectrum over the Pasadena spectrum should show enhanced values in the carbon dioxide portions of the spectrum. Figure 8 shows the ratio of the Mt. Wilson spectrum over the Pasadena spectrum. The enhanced ratio values are evident in the carbon dioxide absorption regions of the spectrum. This simple analysis shows that calibrated AVIRIS spectra are sensitive to the differences in atmospheric carbon dioxide. The differences in this case were caused principally by the difference in path length through the atmosphere for the spectra analyzed. For this case, the AVIRIS spectral region of greatest sensitivity is indicated by the larger ratio values for the carbon dioxide band centered near 2010 nm.

Based on this demonstrated sensitivity, a simple spectral fitting algorithm was developed to attempt to quantify the carbon dioxide abundance in each AVIRIS spectrum. The MODTRAN radiative transfer code was used to calculate a series of high-spectral-resolution spectra for the Pasadena AVIRIS data set with varying amounts of carbon dioxide in the atmosphere. The AVIRIS observation geometry and a 0.25 reflectance surface were used for these calculations. The spectra were convolved to the AVIRIS spectral calibration characteristics, and several are show in Figure 9. To match the MODTRAN spectra to the AVIRIS measured spectra, normalization factors were calculated near 1985 and 2095 nm, respectively, on either side of the carbon dioxide absorption features. These normalization factors were then linearly interpolated for the intervening AVIRIS spectral values. The absolute value of the difference between the AVIRIS measured spectrum and each MODTRAN modeled spectrum was calculated. The carbon dioxide value of the MODTRAN spectrum giving the best fit was reported as the derived value for each AVIRIS spectrum in the Pasadena data set.

Figure 6. Single AVIRIS spectral image from Pasadena, California, region acquired on June 22, 1999. The San Gabriel Mountains are to the left and Pasadena to the right. The data have been spatially average to 80-by-80 m equivalent to enhance the data signal-to-noise ratio.
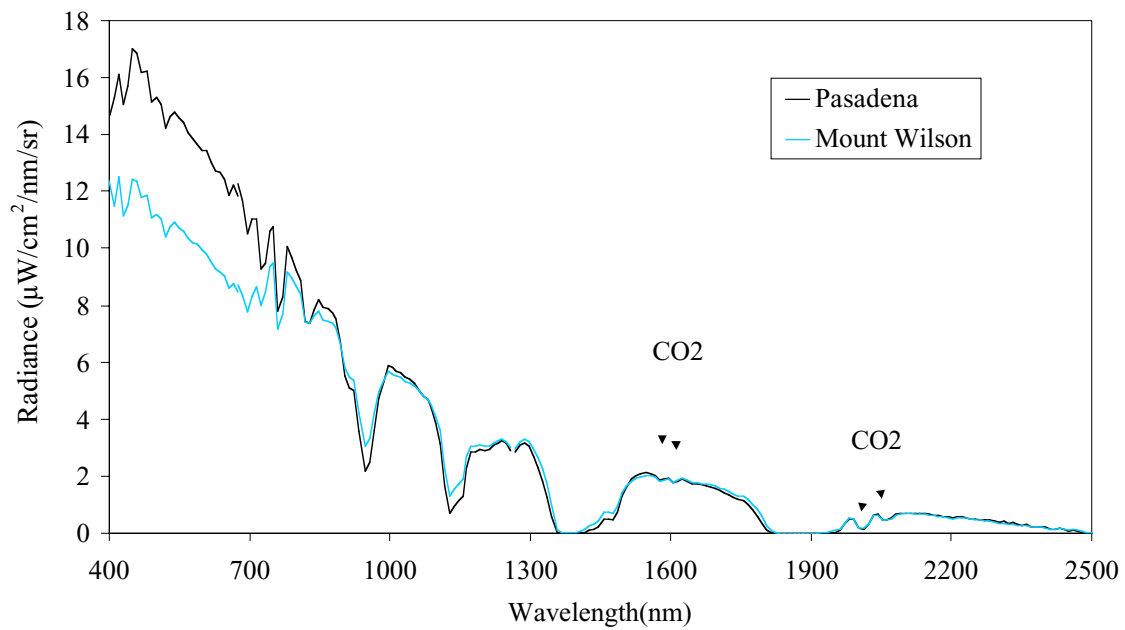
Figure 7. Spectra extracted from Pasadena and Mt. Wilson regions of the AVIRIS data set acquired on June 22, 1999.
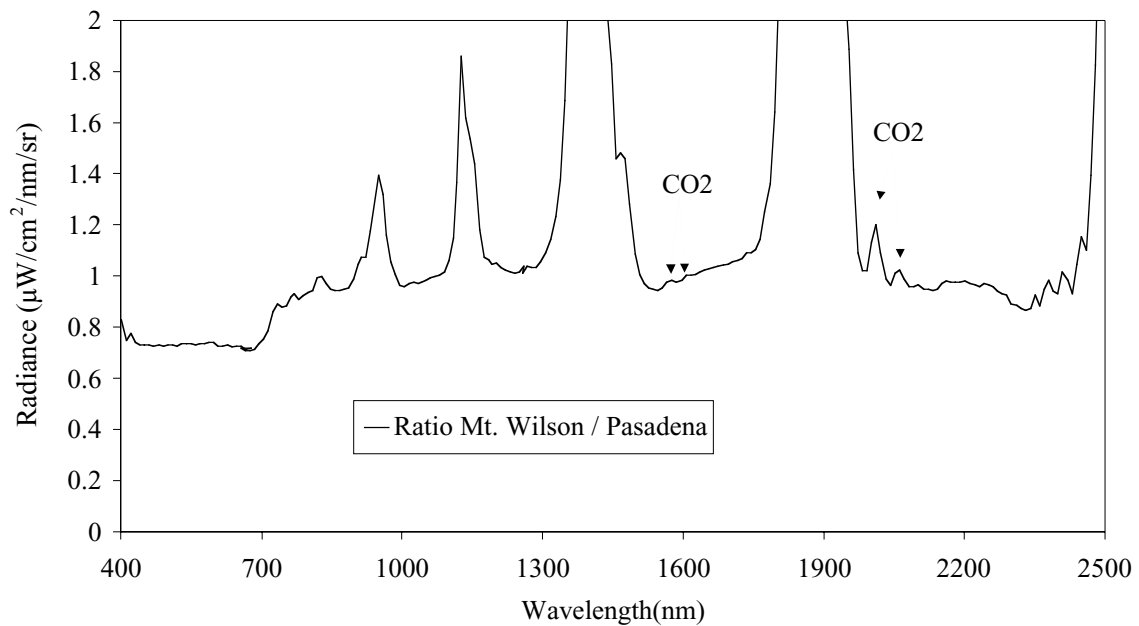

Figure 8. Ratio of AVIRIS Mt. Wilson spectrum to Pasadena spectrum. The enhanced ratio values in the carbon dioxide absorption band show the AVIRIS sensitivity to carbon dioxide abundance. The sensitivity of AVIRIS to water vapor is also clearly shown.
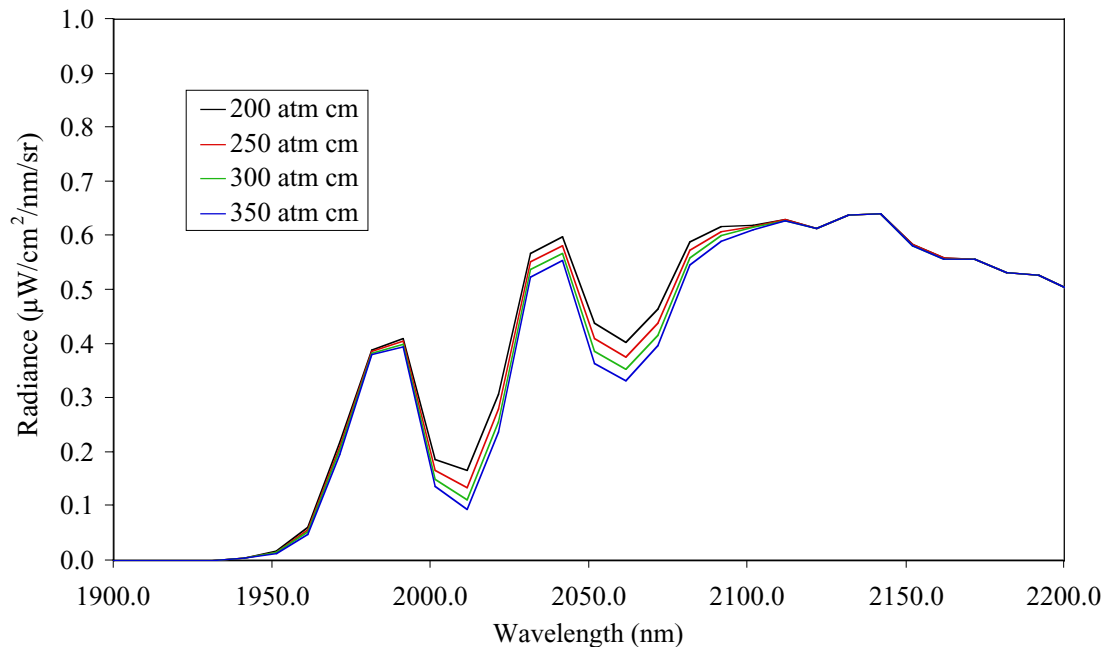
Figure 9. MODTRAN calculated spectra convolved to AVIRIS spectral characteristics for the Pasadena data set observation conditions with differing amounts of carbon dioxide.

An example spectral fit from a Pasadena data set spectrum is shown in Figure 10. The derived carbon dioxide value was 256 atmospheric centimeters (atm cm) for this spectrum. A value of 256 atmospheric centimeters (atm cm) in conjunction with the surface elevation of Pasadena corresponds to an estimated atmospheric mixing ratio of 363 ppm. The full carbon dioxide image for Pasadena is shown in Figure 11. Across the AVIRIS data set, carbon dioxide varied from 160 to 270 atm cm. Lower values were derived in the higher elevation areas of the Mt. Wilson region and San Gabriel Mountains, while higher values were derived in the lower elevation areas of Pasadena and Glendale. This first order variation in carbon dioxide over the data set is attributed primarily to path length variation modulated by surface elevation. The variation in derived carbon dioxide values for adjacent spectra is moderately high. To access this variability, the average and standard deviation of 100 carbon dioxide values in the lower elevation Pasadena portion of the image were calculated. An average of 256 and a standard deviation of 3.41 were found. This corresponds to a nominal 1.3 percent precision for the carbon dioxide retrieval. This variability or noise in the derived carbon dioxide is attributed to a number of factors. These include: the signal-to-noise ratio performance of AVIRIS; the comparatively small change in the spectrum compared to the large background of carbon dioxide in the atmosphere; and residual uncompensated surface reflectance effects. Factors that affect the accuracy of the derivation include: the MODTRAN model and calculations; the simplicity of the fitting algorithm; uncompensated atmospheric aerosols affects; surface reflectance effects; and limitation in AVIRIS spectral and radiometric calibration accuracy. The modification of the spectrum by water vapor also potentially affects the accuracy of the derived carbon dioxide values. These factors and others are planned to be investigated to validate and improve the precision and accuracy of this carbon dioxide derivation approach from AVIRIS measured spectra. However, even with the current implementation, this research has demonstrated the derivation of atmospheric carbon dioxide abundance using AVIRIS measured spectra over a land surface.
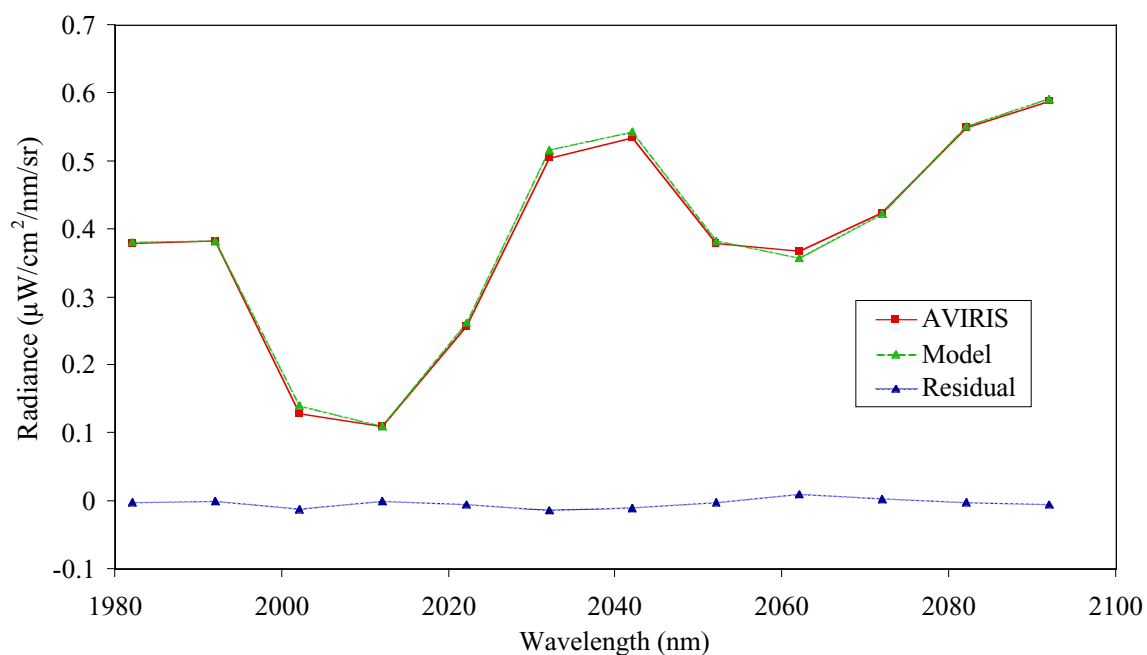
Figure 10. Spectral fit between AVIRIS measured spectrum with MODTRAN-modeled spectrum.
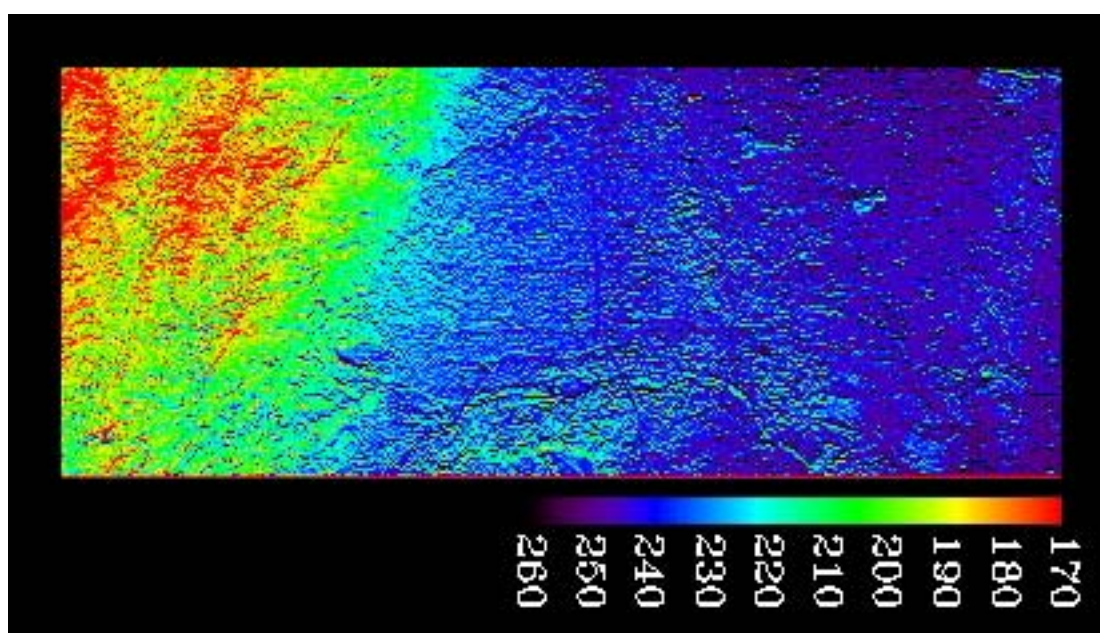

Figure 11. AVIRIS carbon dioxide image in atm cm. Lower carbon dioxide values are derived for the higher elevation regions to the left. Higher values of carbon dioxide are derived at lower elevation in the center and right of the image.

CARBON DIOXIDE OVER WATER

Two thirds of the Earth's surface is covered with water. For any remote sensing strategy for carbon dioxide, it is important to have an approach for water surfaces. Liquid water is a strong absorber at wavelengths longer than 700 nm and effectively absorbs all energy at 1600 and 2000 nm. However, under certain observations sunlight is almost totally reflected from the surface causing sun glint. Sun glint is observed when the angle of observation to the surface is equal and opposite to the angle of solar illumination incidence. The sun glint signal provides a basis for derivation of carbon dioxide over water surface with AVIRIS spectra. On April 12, 2000 AVIRIS acquired an ocean sun glint data set near Hawaii. The data were acquired as AVIRIS turned in a circle to match observation geometry with the SeaWiFS satellite sensor for on-orbit calibration research (Pavri et al., 2000). In a portion of this circular data set, AVIRIS measured the zone of peak sun glint from the ocean surface. Figure 12 shows the sun glint portion of the AVIRIS Hawaii image as well as the dark ocean signal away from the sun glint. The image also contains a number of small clouds. AVIRIS spectra from portions of this image are shown in Figure 13. There is significant signal at the 2000 nm spectral region, and the carbon dioxide absorption features are evident in the sun glint spectrum. The converse is true for the dark ocean spectrum with effectively no expressed signal in the 2000 nm spectral region. The spectral-fitting carbon dioxide algorithm was applied to this data set based upon the good signal available in the sun glint region. The derived carbon dioxide abundance is shown in Figure 14. Nearly uniform values are derived across the image in the sun glint zones. Somewhat lower and more variable values are derived in the dark ocean zones where the signal to AVIRIS is weighted more towards the atmospheric scattered radiation. For the central portion of the sun glint area, an average carbon dioxide abundance of 302 atm cm with a standard deviation of 2.91 atm cm was determined. This yields a precision estimate of 0.96 percent for this AVIRIS data set. The result demonstrates a viable remote sensing strategy for derivation of carbon dioxide abundance in the AVIRIS spectral range of water targets. For a satellite mission, continuous tracking of the sun glint can be achieved with modern pointable satellites.

Figure 12. Portion of an AVIRIS image capturing the sun glint zone acquired on April 12, 2000 near Hawaii.
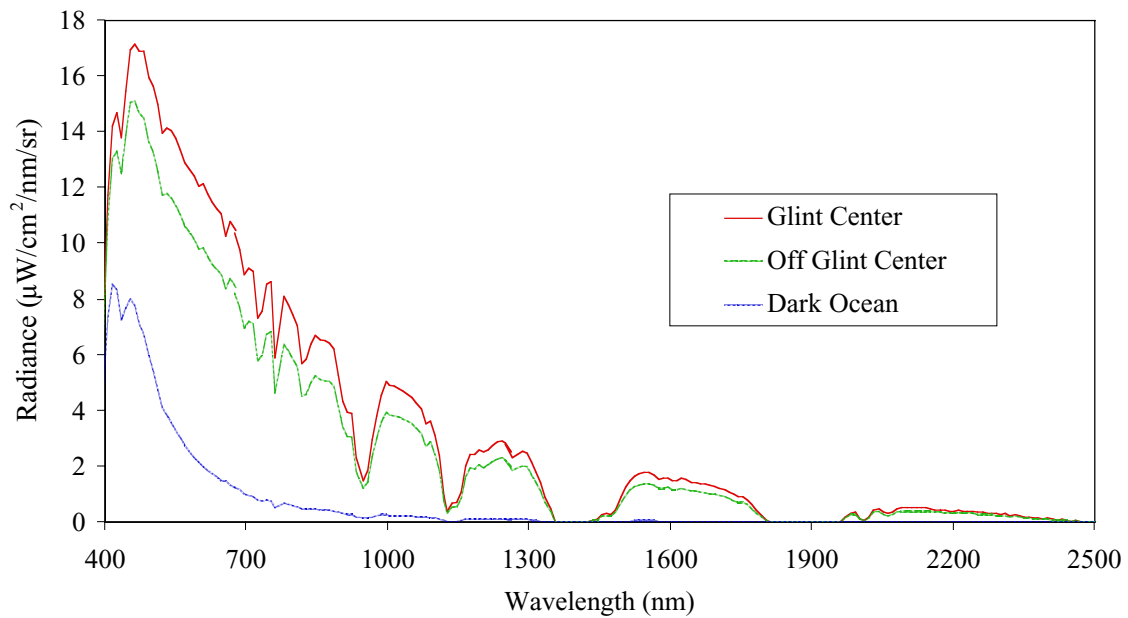
Figure 13. AVIRIS spectra of sun glint off the ocean and adjacent dark ocean.
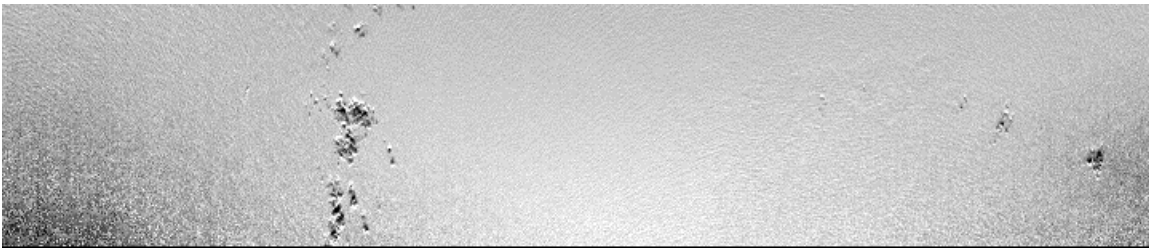

Figure 14. Spectral fitting derived carbon dioxide image from 2000 AVIRIS ocean sun glint data set. A carbon dioxide value of 302 atm cm was obtained with a standard deviation of 2.91 atm cm in the central sun glint region. Clouds high in the atmosphere yield low carbon dioxide values.

CONCLUSION

The spectroscopic expression of carbon dioxide in the AVIRIS spectral range has been shown. Specific carbon dioxide absorption bands are expressed near 1600 and 2000 nm. The MODTRAN radiative transfer code was used to calculate spectra that closely model the spectra measured by AVIRIS. A simple analysis with AVIRIS spectra from two different elevations in a Pasadena, California data set was performed to show that AVIRIS spectra are sensitive to different amounts of carbon dioxide in spectra passing through different paths of the atmosphere. This analysis also showed that the carbon dioxide bands near 2000 nm are more sensitive than the 1600 nm features given the AVIRIS spectral, radiometric, and spatial characteristics. With this demonstrated sensitivity and the MODTRAN radiative transfer code, a spectral-fitting algorithm was developed to derive carbon dioxide from AVIRIS spectra. This algorithm fit MODTRAN spectra calculated with different amounts of carbon dioxide to the AVIRIS measured spectrum. The best-fit result yields a carbon dioxide estimate for each spectrum. The resulting carbon dioxide image of Pasadena shows a consistent result with low values in areas of high surface elevation and high values in areas of low surface elevation. In a homogeneous zone of the Pasadena data

set, an average carbon dioxide abundance of 256 atm cm with a standard deviation of 3.41 was calculated. This leads to an estimated precision of 1.3 for the derivation. Critical factors effecting the precision were identified as the signal-to-noise ratio characteristics of the AVIRIS spectra as well as the uncompensated spectral variation in the surface reflectance. Factors affecting the accuracy were tied to the MODTRAN model, AVIRIS calibration, and simplicity of the algorithm. Research is planned to assess these factors and work to improve the precision and accuracy of the algorithm and derived results. As presented, this research demonstrates the retrieval of carbon dioxide abundance over land surfaces with AVIRIS spectra.

This research was extended to water targets with a data set acquired in Hawaii in the year 2000 containing a strong sun glint signal. Application of the spectral fitting algorithm to this data set derived carbon dioxide values of 302 atm cm with a standard deviation of 2.91. The corresponding estimated precision is 0.96 percent. Many issues remain for research and analysis with this approach to the derivation of carbon dioxide from AVIRIS measured spectra. However, the preliminary results presented here show potential for precise and accurate derivation of carbon dioxide from AVIRIS and AVIRIS like spectral measurement. This class of measurement can, therefore, contribute to the broad scientific research objectives related to carbon dioxide abundance, distribution, sources, and sinks.

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