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# Refinement of wavelength calibrations of hyperspectral imaging data using a spectrum-matching technique

Bo-Cai Gao<sup>a,\*</sup>, Marcos J. Montes<sup>a</sup>, Curtiss O. Davis<sup>b</sup>

<sup>a</sup> Remote Sensing Division, Code 7232, Naval Research Laboratory, Washington, DC 20375, USA <sup>b</sup> Remote Sensing Division, Code 7203, Naval Research Laboratory, Washington, DC 20375, USA

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#### Abstract

The concept of imaging spectrometry, or hyperspectral imaging, is becoming increasingly popular in scientific communities in recent years. Hyperspectral imaging data covering the spectral region between 0.4 and 2.5 µm and collected from aircraft and satellite platforms have been used in the study of the earth's atmosphere, land surface, and ocean color properties, as well as on planetary missions. In order to make such quantitative studies, accurate radiometric and spectral calibrations of hyperspectral imaging data are necessary. Calibration coefficients for all detectors in an imaging spectrometer obtained in a laboratory may need to be adjusted when applied to data obtained from an aircraft or a satellite platform. Shifts in channel center wavelengths and changes in spectral resolution may occur when an instrument is airborne or spaceborne due to vibrations, and to changes in instrument temperature and pressure. In this paper, we describe an algorithm for refining spectral calibrations of imaging spectrometer data using observed features in the data itself. The algorithm is based on spectrummatching of atmospheric water vapor, oxygen, and carbon dioxide bands, and solar Fraunhofer lines. It has been applied to real data sets acquired with airborne and spaceborne imaging spectrometers.

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## 1. Introduction

There are now growing interests in hyperspectral remote sensing for research and applications in a variety of fields, including geology, agriculture, forestry, coastal and inland water studies, environment hazards assessment, and urban studies (Davis et al., 2002; Rencz, 1999). The concept of imaging spectrometry, or hyperspectral imaging, originated from geological communities in the early 1980s (Goetz, Vane, Solomon, & Rock, 1985), mainly for the purpose of mineral exploration. Imaging spectrometers acquire images in many contiguous narrow channels such that, for each picture element (pixel), a complete reflectance or emittance spectrum can be derived from the wavelength region covered. Fig. 1 shows an example of a spectrum acquired with

\* Corresponding author. Remote Sensing Division, Code 7232, Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, DC 20375, USA. Tel.: +1-202-767-3842.

the Airborne Visible Infrared Imaging Spectrometer (AVI-RIS) (Green et al., 1998; Vane et al., 1993) from an ER-2 aircraft at an altitude of 20 km. The solar radiation on the sun-surface-sensor path is subject to absorption and scattering by the atmosphere and the surface. Major atmospheric absorption bands, such as those of water vapor centered at approximately 0.94, 1.14, 1.38, and 1.88  $\mu$ m; the oxygen Aband at 0.76  $\mu$ m; and the carbon dioxide bands near 2.01 and 2.06  $\mu$ m, are present in the spectrum. Additionally, a solar Fraunhofer feature near 0.43  $\mu$ m (principally associated with the H $\gamma$  transition, but there are also a few reasonably strong Fe I lines within the ~10 nm AVIRIS bandwidth; see Lang, 1980) is strong enough to be seen in this spectrum.

In order to study surface properties using imaging spectrometer data, the atmospheric absorption and scattering effects must be removed. Several atmospheric correction algorithms (e.g., Adler-Golden et al., 1998; Gao & Davis, 1997; Gao, Heidebrecht, & Goetz, 1993; Qu et al., 2000) for deriving surface reflectances from imaging spectrometer data have been developed in the past decade.

E-mail address: gao@rsd.nrl.navy.mil (B.-C. Gao).

In the past 15 years, a number of airborne and spaceborne imaging spectrometers have been built using linear detector arrays or area detector arrays in their focal planes. A sensor built with linear detector arrays is commonly referred to as a whiskbroom sensor. For such a sensor, the spectrum of each pixel on the ground is dispersed across the linear array. The spatial imaging is obtained through across track scanning with a scan mirror and forward motion of the aircraft or satellite. AVIRIS is an example of a whiskbroom sensor. A sensor built with area array detectors is often referred as a pushbroom sensor. In such a sensor, one dimension of an array is used for spatial imaging, and the other for spectral imaging. The Hyperion sensor on the NASA EO-1 satellite platform (Ungar, 1997) is an example of a pushbroom sensor. Due to the intrinsic light dispersion properties of grating spectrometers and to minor misalignment of optical components, the wavelengths for pixels near the center of an array and those near the edges of the same array can be slightly different. This is often referred as the "smile" or "frown" effect (Davis et al., 2002; Mourioulis, Green, & Chrien, 2000).

For both the airborne and spaceborne imaging spectrometers, shifts in radiometric and spectral calibrations can occur. Calibration coefficients for all detectors obtained in a laboratory may need to be adjusted when applied to data obtained from an aircraft or a satellite platform. Shifts in channel center wavelengths and changes in spectral resolution may occur when an instrument is airborne or spaceborne due to vibrations, and to changes in instrument temperature and pressure. In order to use radiative transfer-based approach to derive surface reflectances from hyperspectral imaging data for improved studies of surface properties, accurate radiometric and spectral calibration of the data must be achieved (Green, 1998).

Following calibration, atmospheric correction algorithms are typically applied to imaging spectrometer data to remove the effects of atmospheric gas absorption, and Rayleigh and aerosol scattering (e.g., Gao et al., 1993).



Fig. 1. A sample AVIRIS spectrum. Several absorption bands of atmospheric gases are easily seen. The spectrum was acquired over a site in Cuprite, NV, on June 23, 1995.



Fig. 2. Ratio of two simulated transmittance spectra with a sampling interval of about 10 nm, but with wavelengths shifted relative to each other by 1 nm. Each spectral band is described by a Gaussian function with FWHM  $\sim 10$  nm. Over regions where there are absorption bands of atmospheric gases, the ratio deviates significantly from 1.0.

The atmospheric gas absorption features are very sharp and errors in wavelength calibrations can produce significant errors in the retrieved land or ocean surface reflectances around these features. For the purpose of illustrating the importance of wavelength calibrations, we calculated two spectra with the typical AVIRIS spectral parameters, that is, the bands have a spectral sampling interval of about 10 nm, and each band has a Gaussian spectral response function with a full-width at half-maximum (FWHM) of about 10 nm. One spectrum was calculated for the correct wavelengths, and the other with a 1-nm shift in wavelengths for all the channels. Fig. 2 shows the ratio of the two spectra. Over regions near the absorption bands of atmospheric gases, the ratio values deviate significantly from 1. Therefore, small errors in wavelength positions can introduce large errors in the derived reflectance spectra. A spectral calibration accuracy for the channel position and shape of  $\sim 1\%$  of the FWHM is required to remove spectrally distinct errors (Green, 1998).

In this paper, we describe an algorithm for refining spectral calibrations of imaging spectrometer data. The algorithm is based on spectrum-matching of atmospheric water vapor, oxygen, and carbon dioxide bands, and solar Fraunhofer features. Sample results from applications of the algorithm to data acquired with a few airborne and spaceborne hyperspectral imaging sensors are presented.

# 2. Method

Spectrum-matching techniques (Chang & Shaw, 1977) were developed in the 1970s for retrieving positions and widths of atmospheric gases from laboratory-measured "ultra" spectra (in which individual lines within bands of atmospheric gases are resolved). A spectrum-matching technique was later developed for deriving column atmospheric water vapor amounts (Gao & Goetz, 1990) from hyper-

spectral imaging data (in which major bands of atmospheric gases are resolved) acquired with the AVIRIS instrument.

We have recently developed another spectrum-matching algorithm for refining wavelength calibrations of imaging spectrometer data. This algorithm is based on the matching between measured atmospheric water vapor, oxygen, carbon dioxide bands, and solar Fraunhofer features with the corresponding calculated bands. The spectral calculations are performed using procedures described by Gao, Montes, Ahmad, and Davis (2000) and Gao and Davis (1997). In short, the absorption coefficients are pre-calculated using the HITRAN 2000 database (Rothman et al., 1998) and a line-by-line code (W.R. Ridgway, private communication, 1996) for contributions due to  $O_2$ ,  $CH_4$ , CO,  $CO_2$ ,  $N_2O$ , and  $H_2O$  at a high resolution of 0.05 cm<sup>-1</sup>. After accounting for the effects of solar and view geometry, sensor altitude, and ground elevation, the high resolution spectra are convolved to a medium resolution (0.2 nm) spectrum and merged with an  $O_3$  transmittance spectrum also at the 0.2 nm resolution. The merged medium resolution atmospheric transmittance spectrum is convolved to spectral resolution and sampling of any desired instrument. The original solar irradiance spectrum at a resolution of 1 cm<sup>-1</sup> is obtained from the MODTRAN3.5 code (Berk, Bernstein, & Robertson, 1989).



Fig. 3. A flow chart of the wavelength calibration algorithm. Procedures in the double-barred boxes are shown in Fig. 4. NL, NS, and NB are the number of lines (along track), samples (cross-track), and bands (spectrum), respectively.

This spectrum is convolved to a medium-resolution (0.2 nm), and further to the instrument's resolution and spectral sampling. When using solar features to determine the wavelength calibration, we compare the observed radiance (*L*) and solar irradiance at the top of the atmosphere (*E*<sub>0</sub>). When using terrestrial absorptive features, we compare the apparent reflectance  $\rho^*$ , which is defined as

$$\rho^* = \pi L / (\mu_0 E_0), \tag{1}$$

where  $\mu_0$  is the cosine of the solar zenith angle, to the simulated transmittance spectrum. In either case, we normalize both spectra by continuum spectral background levels, which are obtained through linear interpolations. We calculate standard deviation between the measured and simulated spectra. There is an implicit assumption that the surface reflectance is linear, which is reasonable for most substances. The overall algorithm is outlined in Figs. 3 and 4.

In order to illustrate the principle of refining wavelength calibrations, we show in Figs. 5-7 an example of match-

ing an atmospheric oxygen band near 0.76 µm. The solid line in Fig. 5 shows a portion of a continuum-normalized spectrum near 0.76  $\mu$ m, where the atmospheric O<sub>2</sub> A-band absorption occurs. The spectrum was acquired with the Portable Hyperspectral Imager for Low-Light Spectroscopy (PHILLS) (Davis et al., 2002) on May 17, 2000 from an aircraft during a field experiment. The wavelengths for the measured spectrum were based on laboratory calibrations. The dashed line is the calculated transmittance spectrum (also continuum-normalized) corresponding to the solar and viewing geometry. The shapes of the two spectra are quite different, which indicates a possible shift in the wavelength calibration for the PHILLS instrument in the aircraft environment in comparison with the laboratory environment. Because the simulated spectrum was obtained from high resolution line-by-line atmospheric transmittance calculations based on the HITRAN2000 line database and convolved to the 4.52-nm PHILLS spectral resolution, the wavelengths for the simulated spectrum should be correct.



Fig. 4. Flow chart of some component operations referenced in Fig. 3.



Fig. 5. An example of a PHILLS spectrum (solid line) near 0.76  $\mu$ m, where an atmospheric oxygen absorption band occurs, and the simulated spectrum (dashed line) based on laboratory wavelength calibrations of the PHILLS instrument. The scaling is provided by normalizing each spectrum with its continuum.

In order to automate the wavelength calibrations of the PHILLS data based on the oxygen band matching, we assume that the wavelengths of the measured spectrum can shift from -5 to +5 nm in steps of 0.01 nm. For each step, we convolve the high-resolution transmittance spectrum and solar spectrum to the spectral sampling and spectral response function of sensor (PHILLS in this case). The observed spectrum and the simulated transmittance spectrum (or solar spectrum, as appropriate) are continuum normalized across the feature of interest, assuming a linear continuum. We then calculate the standard deviation between the measured and simulated spectra. Fig. 6 shows the standard deviation as a function of wavelength shift. A minimum occurs at a wavelength shift of 2.57 nm. This is considered to be our best estimate of the wavelength shift for the PHILLS spectrum in Fig. 5. The solid line in Fig. 7 shows the same PHILLS spectrum as in Fig. 5, except that the wavelengths are shifted to the right by 2.57 nm. The dashed line in Fig. 7 is the simulated spectrum. The shapes of the two spectra in Fig. 7 are quite similar. Figs. 5-7have demonstrated that, through matching the atmospheric



Fig. 6. The standard deviation between the laboratory calibration spectra and the modeled spectra as a function of wavelength shift.



Fig. 7. A sample PHILLS spectrum (solid line) near 0.76  $\mu$ m with wavelength adjustment based on the matching of the oxygen band, and a simulated spectrum (dashed line).

oxygen band near 0.76  $\mu$ m, it is possible to determine wavelength shift for the PHILLS instrument in the aircraft environment.

In the case of hyperspectral images measured with sensors built with area array detectors, each cross track pixel may have a different wavelength calibration. The spectrummatching technique illustrated above needs to be applied to each pixel in the cross track direction. In our practical applications, we average all spectra in each along track column of a scene to improve signal-to-noise ratio, and apply the spectrum-matching technique to the averaged spectrum to obtain an estimate of wavelength shift for the column. The process is repeated for every along track column in the imaging scene.

Through analysis of measured imaging spectrometer data, we have found that a number of atmospheric and Fraunhofer bands in the 0.4–2.5  $\mu$ m spectral region can be useful for wavelength calibrations using the spectrum-matching technique described above. Specifically, for instruments with a spectral resolution of approximately 10 nm, the atmospheric water vapor bands centered near 0.82, 0.94, 1.14 µm, the oxygen band near 0.76 µm, and the carbon dioxide bands near 1.58 and 2.06 µm can be used for wavelength calibrations. For instruments with a spectral resolution of about 5 nm, the Hy solar Fraunhofer line near 0.43 µm (approximate width W=0.3 nm) becomes useful due to the increased resolving power of the instruments. For instruments having a spectral resolution of 2.5 nm or better, solar Fraunhofer features centered near 0.517  $\mu$ m (several lines, each with  $W \sim 0.1$ nm, due to Mg I), 0.656  $\mu$ m ( $W \sim 0.4$  nm, H $\alpha$ ), 0.854  $\mu$ m  $(W \sim 0.4 \text{ nm}, \text{Ca II})$ , and 0.866  $\mu \text{m}$  ( $W \sim 0.3 \text{ nm}, \text{Ca II}$ ), can be used for wavelength calibrations because of the further increased resolving power of the instrument.

### 3. Results

Our spectrum-matching algorithm for refining wavelength calibrations has been applied to hyperspectral data



Fig. 8. AVIRIS wavelength offsets derived through spectrum-matching of an oxygen band near 0.76  $\mu$ m (small dashes), a water vapor band near 1.14  $\mu$ m (solid line), and a carbon dioxide band near 2.06  $\mu$ m (long dashes).

collected with several imaging spectrometers. Sample results from applications to AVIRIS, PHILLS, and Hyperion data are described below.

# 3.1. AVIRIS

AVIRIS is an airborne imaging spectrometer designed and built at the Jet Propulsion Laboratory (Green et al., 1998; Vane et al., 1993). It simultaneously images in 224 contiguous spectral bands, covering the 0.4-2.5 µm wavelength region. It is flown on either a NASA ER-2 aircraft at a high altitude of about 20 km, or an NOAA Twin Otter aircraft at low and variable altitudes. AVIRIS actually contains four separate spectrometers named Spectrometers A, B, C, and D, respectively. In the focal plane for each of the four spectrometers, one line array of detectors is used for recording spectrally resolved radiances for a given picture element on the ground (pixel). The spatial imaging is obtained through forward aircraft motion and across track scanning with a scan mirror. AVIRIS is classified as a whiskbroom sensor. A standard AVIRIS data set is a three-dimensional data cube. It has 614 pixels in the cross-track direction, 512 pixels in the along-track direction, and 224 spectral bands for each pixel. In principle, the spectral calibrations for every spectrum in an AVIRIS scene should be the same, because the same line detector arrays are used to record a spectrum for every pixel in the image.

Before applying our spectrum-matching technique to AVIRIS data, we typically average all the 512 spectra in one along track column of a scene to obtain a spectrum with signal-to-noise ratios well above 1000. The spectrum-matching technique is then applied to the averaged spectrum to estimate wavelength shift relative to the laboratory-calibrated wavelengths. Sample wavelength shifts obtained from an AVIRIS data set are shown in Fig. 8. The AVIRIS data used in this study were acquired over the Cuprite (30°30' N and 117°10' W) mining district in Nevada on

June 23, 1995. The three curves in Fig. 8 are wavelength shifts as a function of sample number (cross track direction). These wavelength shifts are obtained through matching an atmospheric oxygen band near 0.76 µm, a water vapor band near 1.14 µm, and a carbon dioxide band near 2.06 µm. Both the oxygen and the water vapor bands are located in the wavelength region covered by Spectrometer B of AVI-RIS. The carbon dioxide band is located in the wavelength range covered by Spectrometer D. The mean of wavelength shifts from fitting the oxygen band for all the samples is -0.589 nm with a standard deviation of 0.011 nm. This mean shift is well within the AVIRIS' laboratory wavelength calibration uncertainty of  $\pm 1$  nm. Because AVIRIS is a scanning instrument, the shift is essentially the same across the scene. The mean shift can be considered to be the best estimate of AVIRIS' wavelength shift based on the oxygen-band-fitting. The standard deviation of 0.011 nm can be considered to be the precision with this method for the AVIRIS data. The mean wavelength shift obtained from fitting the 1.14- $\mu$ m water vapor band is -0.658 nm with a standard deviation of 0.017 nm. This mean shift is consistent with the mean shift obtained from fitting the oxygen band. The mean shift derived from fitting the CO<sub>2</sub> band near 2.06  $\mu$ m is +0.344 nm with a standard deviation of 0.010 nm. The wavelength shift for Spectrometer D is positive while that for Spectrometer B is negative. The amounts of shifts are all well within the stated AVIRIS' laboratory calibration accuracy of  $\pm 1$  nm.

The AVIRIS instrument is serviced and modified once per year. The laboratory wavelength calibration for each band changes from year to year. Therefore, offsets derived from this algorithm should also change as the spectral calibration changes. Since AVIRIS is a stable instrument, we expect to get similar offsets within the same flight season. In order to investigate these properties, we also obtained AVIRIS data sets from the 1997 flight season, in addition to the 1995 AVIRIS data set described above. The first two rows of Table 1 show a comparison of how the wavelength offsets change from year to year, using offsets derived from both the aforementioned 1995 Cuprite data and the June 19, 1997 Cuprite data. We see that there is a significant difference for all three transitions, much greater than the precision (standard deviation). On June 23, 1997, AVIRIS acquired data from the Lunar Lake region (38°24' N, 115°59' W) in

Table 1

A comparison of derived offsets using AVIRIS data from two different years and from two different dates in the same year

Location and year	O <sub>2</sub> A-band B spectrometer		H <sub>2</sub> O 1.14 μm B spectrometer		CO <sub>2</sub> 2.06 μm D spectrometer	
	Cuprite 1995	-0.589	0.011	-0.658	0.017	0.344
Cuprite 1997	-0.247	0.015	-0.284	0.031	0.164	0.006
Lunar Lake 1997	-0.272	0.010	-0.341	0.028	0.086	0.010

Nevada; the derived offsets are listed in the third row of Table 1. The two flights in 1997 have very similar offsets for the three transitions, with the differences between the two 1997 scenes being less than 0.1 nm in all cases. This can be considered to be an estimate of the accuracy of this method using the 1997 AVIRIS data sets.

One of the principle goals of determining a better spectral calibration is to obtain an improved surface reflectance spectrum by removing the atmospheric absorption and scattering effects. An atmospheric correction of the 1995 AVIRIS Cuprite scene was performed using a modified version of the Atmosphere Removal Algorithm (ATREM) (Gao & Davis, 1997; Gao et al., 1993). The solid line in Fig. 9 shows the surface reflectance spectrum for the range covered by the B-spectrometer and derived from the radiance spectrum in Fig. 1. The appropriate offset for the Bspectrometer was determined by averaging the offsets obtained from the  $O_2$  and  $H_2O$  (1.14 µm) features shown in Fig. 8. This offset was then added to the laboratory calibration values of the B-spectrometer (bands 33-96), and the atmospheric correction was performed again. The dashed line in Fig. 9 shows the improved surface reflectance retrievals. The curve is now much smoother, and the spurious features around the oxygen and water vapor absorption bands have been mostly removed.

## 3.2. PHILLS

Over the past few years, the Naval Research Laboratory (NRL) has built a series of PHILLS instruments (Davis et al., 2002, 1999). All the PHILLS instruments use area array focal planes. The PHILLS instruments have a perpixel spectral resolution of 1.13 nm and are typically binned by 4 to 4.52 nm. Data collections have been made from low-altitude airborne platforms during several field



Fig. 9. Atmospherically corrected reflectance spectra for a portion of the AVIRIS B-spectrometer for the same pixel as in Fig. 1. The results using the laboratory spectral calibration are shown using a solid line. The results after applying the derived wavelength offset are shown with a dotted line. The spurious features around the 0.76- $\mu$ m oxygen band and the 0.94- $\mu$ m water vapor band are mostly eliminated.



Fig. 10. PHILLS wavelength offsets based on fitting an oxygen band near  $0.76 \,\mu\text{m}$  (bottom line) and a solar Fraunhofer feature near  $0.431 \,\mu\text{m}$  (top line).

experiments. The temperature and pressure around the PHILLS instruments have not been controlled during the data acquisitions. Our spectrum-matching technique has been applied to the column-averaged PHILLS spectra for estimating wavelength offsets. Sample results obtained from one PHILLS data set are shown in Fig. 10. The PHILLS data with a spectral resolution of 4.52 nm were acquired over an area in New Jersey (39°20' N and  $74^{\circ}30'$  W) on July 31, 2001. The two curves in Fig. 10 are wavelength offsets (as a function of sample number in the cross track direction) derived through matching the oxygen band near 0.76 µm and a solar Fraunhofer feature near 0.43 µm. The offset curve from the oxygen band matching shows a difference of about 0.7 nm from left side of the detector array to the right side of the array. This is the result of a combination of spectral smile of about 0.3 nm over 1000 pixels and a tilt of about 0.6 nm over 1000 pixels caused by misalignment between the spectrometer and the camera. The two curves in Fig. 10 have a vertical offset of approximately 1.3 nm, indicating a possible change in light dispersion property for the PHILLS instrument in the aircraft environment.

## 3.3. Hyperion

The Hyperion instrument was built by TRW Space, Defense and Information Systems in Los Angeles, CA. It is the first spaceborne earth observing imaging spectrometer flying on a NASA experimental satellite platform named Earth Observer-1 (EO-1) (Ungar, 1997). This instrument was launched into space in November 2000. It covers the  $0.4-2.5 \mu m$  spectral range with more than 220 narrow channels at a spectral sampling interval and FWHM of about 10 nm. It has a spatial sampling of 30 m on the ground, and a surface swath width of 7 km (Ungar, 1997). The dashed line in Fig. 11 shows the center wavelength position for band 41 as a function of sample number in the satellite cross track direction. The center wavelengths were obtained based on laboratory calibrations of the Hyperion



Fig. 11. Center wavelengths as a function of sample number in the cross track direction for Channel 41 of the Hyperion instrument obtained from laboratory calibration (dashed line) and retrieved from the Cuprite Hyperion data set (dotted line) and from the Coleambally Hyperion data set (solid line) based on spectrum-matching of the oxygen band near 0.76 μm. The spurious features around the 0.76-μm oxygen band and the 0.94-μm water vapor band are mostly eliminated.

sensor at TRW. Because the center wavelength of each band depends on the sample number, the "smile" effect is clearly present in the Hyperion sensor.

On March 1, 2001, Hyperion acquired data from the Cuprite mining district in Nevada. Over the years, this area has been extensively studied using both remote-sensing data (e.g., from AVIRIS), as well as with on-site field measurements (Goetz et al., 1985). This area has very little vegetation. It contains many types of minerals. The dotted line in Fig. 11 is a curve of our estimated center wavelength positions based on applying our algorithm to this scene using the 0.76- $\mu$ m oxygen band. This curve is shifted upward by roughly 1 nm in comparison with the laboratory calibration curve, and the amount of the shift varies with the cross-track sample number.

On March 6, 2001, Hyperion acquired data from the Coleambally Irrigation Area  $(39^{\circ}48' \text{ S}, 145^{\circ}39' \text{ E})$  in southern Australia. Field measurements were obtained as a part of the agricultural component of Hyperion validation. The area consists of a patchwork of large agricultural fields. Crops that were growing at the time include rice, corn, and soybeans. Additionally, either crop stubble or bare soil was present in some of the fields. The solid line in Fig. 11 is the estimated center wavelength positions for band 41 based on applying our algorithm to this scene using the 0.76- $\mu$ m oxygen band.

It is seen from Fig. 11 that our derived calibrations for Hyperion's band 41 for the two scenes, Cuprite and Coleambally, agree quite well. This demonstrates that our algorithm is able to properly take account of the effects of spectral variations for very different types of surface targets. In particular, our algorithm utilizing the oxygen A-band performs consistently over both the desert Cuprite site and the vegetated Coleambally site. The mean difference between the derived calibrations for two sites provides an estimate of the accuracy of our method. We estimate an overall accuracy (including all errors, such as spectral simulation and spectral background renormalization) of about 0.1 nm for this sensor using the  $O_2$  A-band transition. The accuracy measured in this manner also inherently includes any systematic effects relating to the temperature of the spacecraft at different points of its orbit. In the northern hemisphere, Hyperion just came out of the Earth's shadow; while in the southern hemisphere, Hyperion was already in the sunlight for some time and the instrument temperature increased.

## 4. Discussion

During the past decade, other researchers have also used terrestrial as well as solar atmospheric absorption features to improve wavelength calibrations. For example, Green (1995) used surface reflectance data measured over the Lunar Lake calibration site as input data to the MODTRAN atmospheric radiative transfer code. He compared the AVI-RIS-measured and MODTRAN-predicted radiances in order to verify AVIRIS' laboratory spectral calibrations. Goetz, Heidebrecht, and Chrien (1995) performed an analysis of the AVIRIS B-spectrometer's spectral calibration using the O<sub>2</sub> A-Band. The wavelength shift was derived on a pixel-bypixel basis and the resultant histogram of the wavelength shifts was used to estimate a mean shift for the entire scene. The analysis by Barry, Shepanski, and Segal (2001) focused on the spectral calibration of Hyperion's SWIR focal plane. They used solar radiances reflected off the inside cover of the Hyperion instrument. Qu, Goetz, and Heidebrecht (2000) determined the spectral shift by using a smoothness criterion on the derived surface reflectance spectrum as a part of an atmospheric correction algorithm. As with Qu et al. and Goetz et al., our algorithm uses observed data without the need of surface reflectance measurements in order to derive the wavelength shift parameters. This is particularly advantageous when the ground truth data simultaneous with imaging spectromer's overflights are difficult to obtain.

The application of our algorithm to AVIRIS data has demonstrated that the channel positions can be estimated with a precision of 0.03 nm or better using our spectrummatching technique. Additionally, applying this algorithm to data from sites on two dates in 1997 yielded consistent offsets that varied by < 0.1 nm, while the AVIRIS' laboratory calibration uncertainty is about  $\pm 1$  nm. Therefore, improved wavelength calibrations can be obtained using the spectrum-matching technique. After adjusting the standard AVIRIS wavelength calibration based on our results, errors in derived surface reflectance spectra using atmospheric correction algorithms are decreased significantly (Fig. 9), particularly over spectral regions where the atmospheric gas absorption features are strong (see Figs. 1 and 2).

For array spectrometers, the spectral calibration may vary across the scene as a result of spectral smile or misalignment. The applications of our spectrum-matching algorithm to the PHILLS data and Hyperion data have shown that our algorithm is sufficiently accurate to allow the measurement of these artifacts. Corrections of these artifacts, in particular the misalignment, are possible for airborne and spaceborne imaging spectrometers.

Our algorithm is best applied to scenes with uniform atmospheric properties due to spatial averaging of data in the along track direction for increasing the signal-to-noise ratio. Imaging data acquired over water surfaces should be avoided because of much lower signal-to-noise ratio of the data, particularly at wavelengths longer than 0.8 µm. The assumption of linearity in surface reflectance spectra is generally valid for the particular transitions being investigated. Care should be taken when choosing parameters to determine the amount of water vapor (see Table 2 of Gao et al., 1993). The non-linearity of the transmittance as a function of column water vapor will make it difficult to derive accurate offsets using the water vapor features when there are large variations in water vapor content across a scene. For a similar reason, large variation in liquid water content in plants throughout the scene will also cause problems in determining offsets using the atmospheric water vapor bands. A proper radiometric calibration is also needed in order to use our spectrum-matching technique for wavelength calibrations. Systematic errors in the radiometric calibrations of the bands used to determine wavelength offsets will appear in the retrieval results. For example, a mis-calibration of Hyperion's band 39, sample 177 shows as the downward spike in the derived offset from both the Coleambally and Cuprite curves in Fig. 11.

### 5. Summary

We have developed a spectrum-matching algorithm for refining the wavelength calibrations of imaging spectrometer data. Atmospheric water vapor, carbon dioxide, oxygen bands, and solar Fraunhofer features are used for spectrummatching. This algorithm can be used with data acquired for a typical hyperspectral imaging data set. The algorithm has been applied to data acquired over a variety of locations, with the AVIRIS, PHILLS, and Hyperion instruments onboard aircraft or satellite platforms. After the refinement in wavelength calibrations, improved derivation of surface reflectance spectra from hyperspectral imaging data based on radiative transfer modeling can be obtained. Subsequently, better studies of surface properties using the derived surface reflectance spectra can be conducted.

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