COMPARISON OF ATREM, ACORN, AND FLAASH ATMOSPHERIC CORRECTIONS USING LOW-ALTITUDE AVIRIS DATA OF BOULDER, CO

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1.0 Introduction

Three atmospheric correction software packages, the Atmospheric REMoval program (ATREM), Atmospheric CORrection Now (ACORN), and the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) were evaluated for correction of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data to reflectance for several flightlines over the city of Boulder, Colorado. AVIRIS data were corrected using similar parameters and options for each software. Results were compared by examining extracted reflectance spectra for known locations with field spectral measurements made with an Analytical Spectral Devices (ASD) Fieldspec Pro field spectrometer. This paper describes software/algorithm characteristics, correction results, and performance. Examples of corrected data are presented.

2.0 Background

Atmospheric correction is a prerequisite to most Hyperspectral Imagery (HSI) data analysis approaches. Both empirical and model-based correction methods are available, however, we only evaluated selected model-based methods in this study. Three model-based atmospheric correction methods were evaluated: 1) ATREM, 2) ACORN, and 3) FLAASH. All of these basically follow the radiative transfer model shown below (Gao and Goetz, 1990), though each model uses a slightly different version and the FLAASH algorithm adds a term to account for adjacency effects (Adler-Golden et al., 1999).

$$L_0(\lambda)=L_{sun}(\lambda)\ T(\lambda)\ R(\lambda)\ \cos(\theta) + L_{path}(\lambda) \qquad (1)$$

Where

(λ)= wavelength
$L_0(\lambda)$=observed radiance at sensor
$L_{sun}(\lambda)$ = Solar radiance above atmosphere
$T(\lambda)$ = total atmospheric transmittance
$R(\lambda)$ = surface reflectance
θ =incidence angle
$L_{path}(\lambda)$ = path scattered radiance

Current atmospheric correction programs assume that the surface is horizontal and has a Lambertian reflectance. This is because for real data we typically don't have enough information to make the topographic [$\cos(\theta)$] correction. The end result is called "scaled surface reflectance" or "apparent reflectance". The scaled surface reflectance can be converted to surface reflectance if the surface topography is known.

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2.1.1 ATREM

ATREM is software developed by the University of Colorado for retrieving scaled surface reflectance from hyperspectral data using a radiative transfer model (Gao and Goetz, 1990; Gao et al., 1993; CSES, 1999). First the solar zenith angle is derived based on the AVIRIS acquisition time, date, and geographic location. Atmospheric transmittance spectra are derived for each of seven atmospheric gases [water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), nitrous oxide (N_2O), carbon monoxide (CO), methane (CH_4), and oxygen (O_2)] using the Malkmus narrow band model (Malkmus, 1967). A water vapor “lookup table” is created by generating modeled spectra for various water vapor concentrations, again using the Malkmus narrow band model and estimating the 0.94 and/or 1.13 micrometer water vapor band depths for each spectrum. Band depths are determined using a ratio of the band center to the two band shoulders. Water vapor is then estimated for each AVIRIS pixel by determining the band depth and comparing to the modeled band depths in the lookup table. The output of this procedure is an image showing the spatial distribution of various water vapor concentrations for each pixel of the AVIRIS data. Atmospheric scattering is modeled using the “6S” radiative transfer code, (Tanre et al., 1986). Apparent reflectance spectra are obtained by dividing each AVIRIS spectrum by the solar irradiance curve above the atmosphere (Kneizyx et al., 1983) and using the water vapor image along with the other atmospheric parameters in the radiative transfer model of Tiellet (1989). The final results are a water vapor image and reflectance-corrected AVIRIS data without use of ground spectral measurements. While the ATREM software package is no longer supported and is not available to new users, many HSI data users have and use ATREM. It demonstrates baseline atmospheric correction capabilities. ATREM Version 3.1 was the last publicly released software and was used for this research (CSES, 1999).

2.1.2 ACORN

ACORN is a commercially-available, enhanced atmospheric model-based software that uses licensed MODTRAN4 technology (Berk et al, 1999) to produce high quality surface reflectance without ground measurements. The package provides an atmospheric correction of Hyperspectral and Multispectral data measured in the 0.4 - 2.5 micrometer spectral range (AIG, 2001). ACORN uses look-up-tables calculated with the MODTRAN4 radiative transfer code to model atmospheric gas absorption as well as molecular and aerosol scattering effects, converting the calibrated sensor radiance measurements to apparent surface reflectance (AIG, 2001). The well mixed gases are constrained by the elevation and the observation geometry. Water vapor is estimated from the data on a pixel-by-pixel basis using the water vapor absorption bands at 0.94 and/or 1.150 micrometers. A lookup table for a range of water column vapor densities is generated using MODTRAN4 and then fitted in a least-squares sense against the imaging spectrometer data. A key feature of ACORN is full spectral fitting to solve for the overlap of absorptions between water vapor and liquid water in surface vegetation. Visibility is estimated from the AVIRIS data using nonlinear least-squares spectral fitting between the AVIRIS radiance spectra and MODTRAN modeled radiance with the aerosol optical depth as the primary fitting parameter. The two-way transmitted radiance and atmospheric reflectance are calculated for each pixel using MODTRAN and the derived water vapor, pressure elevation, and aerosol optical depth estimations. Apparent surface reflectance is derived from the total upwelling spectral radiance for a given atmosphere using a variant of the radiative transfer equation (1) (Green et al., 1996). The principal outputs of ACORN are a water vapor image and a scaled surface reflectance cube. An image showing an estimate of leaf-water is also optionally produced. ACORN artifact suppression options include automated wavelength correction, removal of noisy channels, and “polishing” of residual errors. The latest version, ACORN 4.15 was used for this research.

2.1.3 FLAASH

FLAASH is a MODTRAN4-based atmospheric correction software package developed by the Air Force Phillips Laboratory, Hanscom AFB and Spectral Sciences, Inc (SSI) (Adler-Golden et al., 1999). It provides accurate, physics-based derivation of apparent surface reflectance through derivation of atmospheric properties such as surface albedo, surface altitude, water vapor column, aerosol and cloud optical depths, surface and atmospheric temperatures from HSI data. FLAASH operates in the 0.4 – 2.5 micrometer spectral range. First, MODTRAN simulations of spectral radiance are performed for various atmospheric, water vapor, and viewing conditions (solar angles) over a range of surface reflectances to establish lookup tables for the atmospheric parameters of column water vapor, aerosol type, and visibility for subsequent use. Typically, the 1.13 micrometer water band is used to estimate water vapor, and a ratio of in-band and out-of-band radiance values allows estimation of absorption band depths for a range of water vapor column densities. FLAASH also derives pressure altitudes by applying the same method to the oxygen 0.762 micrometer absorption band. The radiance spectra are extracted from the AVIRIS data and compared against the MODTRAN lookup tables on a pixel-by-pixel basis to determine scaled surface reflectance. FLAASH offers the additional option of correcting for light scattered from adjacent pixels. Spatially averaged reflectance is used to account for the “adjacency effect’’ - radiance contributions that, because of atmospheric scattering, originate from parts of the surface not in the direct line of sight of the sensor (Adler-Golden et al., 1999; Mathew et al., 2003). FLAASH provides additional flexibility when compared to the other two atmospheric correction programs in that it allows custom radiative transfer calculations for a wider range of conditions including off-nadir viewing and all MODTRAN standard aerosol models.

2.1.4 Post Processing and Use of Field Calibration Measurements:

While all of the above atmospheric correction models produce apparent surface reflectance without *a-priori* knowledge or requiring field measurements, the corrected spectra often contain residual artifacts not corrected by the models. ATREM data can be “polished” using “EFFORT”, a routine designed to remove these artifacts using a fit to “smooth” HSI spectra to determine gains and offsets for each spectral band (Boardman, 1998). Both ACORN and FLAASH also include the option to polish the spectra using methods similar to EFFORT. Finally, if field spectra have been measured for targets occurring in the HSI data, then the model-corrected spectra can be further refined by determining a multiplier to match the HSI spectra to the field spectra and applying on a per-pixel basis. We looked at unpolished, polished, and field-corrected AVIRIS data as part of this study.

3.0 Approach

Our approach to analysis of these data was to apply each of the model-based atmospheric correction methods to AVIRIS data to produce surface scaled reflectance, attempting as best as possible to match the input parameters between models. All models were run using the approximately 1.13 micrometer water vapor band. Six different atmospheric correction results were calculated and compared for this research for 3.8m Boulder AVIRIS data (AVIRIS Line 9, Run 08, 14 October 2004): 1) ATREM, 2) ATREM with "EFFORT" polishing, 3) ACORN, 4) ACORN with polishing, 5) FLAASH, and 6) FLAASH with polishing. We also used field reflectance measurements to refine the atmospheric corrections for improved spectral analysis, however, those results are not discussed here.

4.0 Results

AVIRIS data were originally delivered to Horizon GeoImaging, LLC as geocorrected, calibrated radiance data (the AVIRIS standard product). Ground calibration sites/targets were chosen on the geocorrected data. Non-Geocorrected data were obtained from JPL and the corresponding selected ground locations inversely mapped to these data. All atmospheric corrections and analyses of the AVIRIS data were performed on the non-geocorrected data. Final results were orthorectified using algorithms developed by Analytical Imaging and Geophysics, LLC (Boardman, personal communication, 2004).

4.1 Radiance Data

Figure 1 shows a few representative radiance spectra extracted for Regions of Interest (ROIs) from the Line 9, Run 08, 3.8m AVIRIS data for two sites (The Boulder Rifle Club and Centennial Middle School). Radiance spectra are from the corresponding pixels on the non-geocorrected data.

Figure 1: Left is geocorrected AVIRIS grayscale image (Band 31, 0.66 micrometers) of the Boulder Rifle Club site with colored ROIs overlain. ROIs were selected based on field measurements. Red is a gravel/sand parking lot (Gravel #1). Green is a sandy gun-range gravel (Gravel #2). Blue is a galvanized metal building. Center is geocorrected AVIRIS grayscale image (Band 31, 0.66 micrometers) of the Centennial Middle School site with colored ROIs selected based on field measurement sites overlain. Magenta is a sandy gravel parking lot. Sea Green is a yellow school bus. Yellow is an asphalt driveway. Maroon is a green grassy athletic field. Purple is the green portion of a synthetic tennis court surface. Orange is the red portion of a synthetic tennis court surface. Right is spectral plot of selected Mean AVIRIS Radiance Spectra (Rifle Club gravel #1, gravel #2, galvanized building and Centennial Middle School sandy gravel parking lot and green grassy athletic field) with colors matching ROI overlay colors.

4.2 Correction Results Overview

All three model-based atmospheric correction methods produced useable HSI spectra with characteristic reflectance spectrum shapes (Figure 2). Note similarities of basic model-corrected spectra (left spectra), but the presence of small "spikes". The right spectra result from "polishing", which removes spikes that occur in all spectra using a gain and offset correction. Differences near 1.4 and 1.9 micrometers are caused by low signal caused by nearly total absorption by water vapor. It's interesting to note that while based on slightly different atmospheric models and procedures, ATREM, ACORN, and FLAASH produce very similar results.

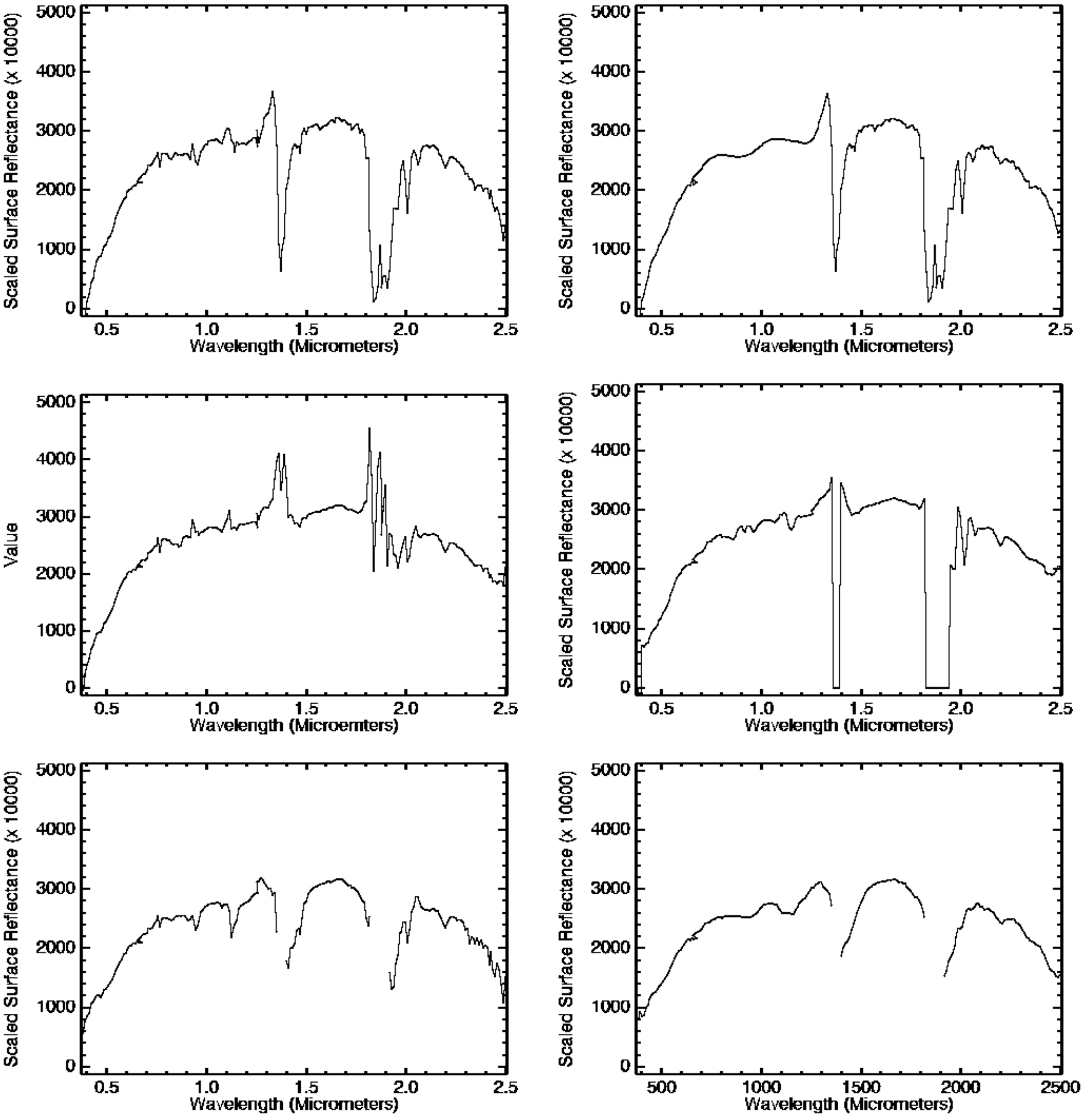


Figure 2: AVIRIS mean reflectance spectra (N=11) for a typical Boulder, Colorado gravel (Boulder Rifle Club Gravel #2), produced using ATREM, ACORN, and FLAASH for the Line 9, Run 08 (3.8m spatial resolution) AVIRIS data. Top row shows ATREM spectra, middle row ACORN spectra, and bottom row FLAASH spectra. Left column shows model-corrected spectra and the right column polished spectra.

4.3 Additional Atmospheric Correction Products:

Several other products were produced in addition to the corrected surface reflectance data using the atmospheric corrections. A water vapor image is calculated by ATREM, ACORN, and FLAASH for use in the atmospheric model. This image shows the total column water vapor (in cm) for each image pixel. ACORN also optionally produces a liquid water image, while FLAASH also produces a cloud mask. Figure 3 shows examples of these images (geocorrected) for the Boulder Line 9, run 8 (3.8m) data.

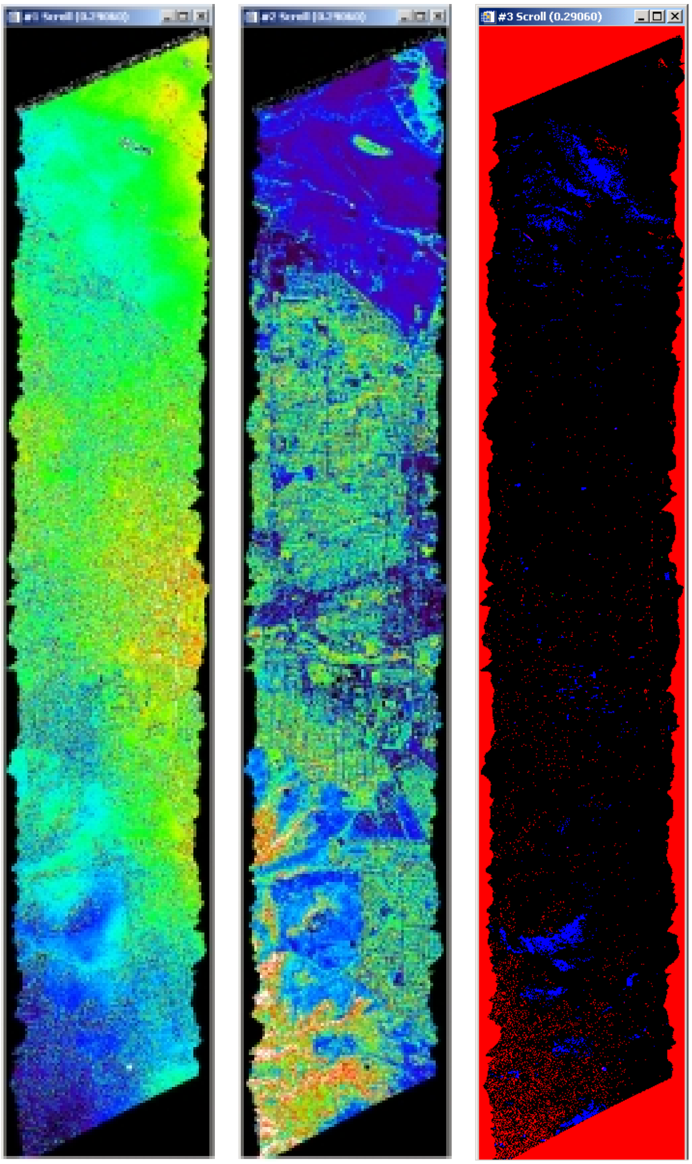


Figure 3: Left - ACORN water vapor image (also available from ATREM, FLAASH). Center - liquid water image (ACORN only). Standard rainbow color scheme is used for left and center images. Blue indicates low water contents. Green, yellow, red, white indicate progressively higher water contents. Right - cloud mask (FLAASH only) shows areas with high altitude (cirrus) clouds as blue and water retrieval errors as red. In this case the geocorrected border accounts for most water retrieval errors. Most of the cloud mask here appears to correspond to areas of bright soils.

4.4 Comparison of Atmospheric Correction Results (3.8m AVIRIS data)

The model-corrected reflectance spectra were all similar for specific materials and generally matched known spectra, as judged by comparison to field spectral measurements (Figure 4). The corrected were generally within approximately 5% absolute reflectance excluding the atmospheric absorption bands. Performance was considerably better at many wavelengths. (Figure 4). The worst absolute matches were for the SWIR region (2.0 – 2.5 micrometers), however, the spectral shapes and absorption bands match well even in this region.

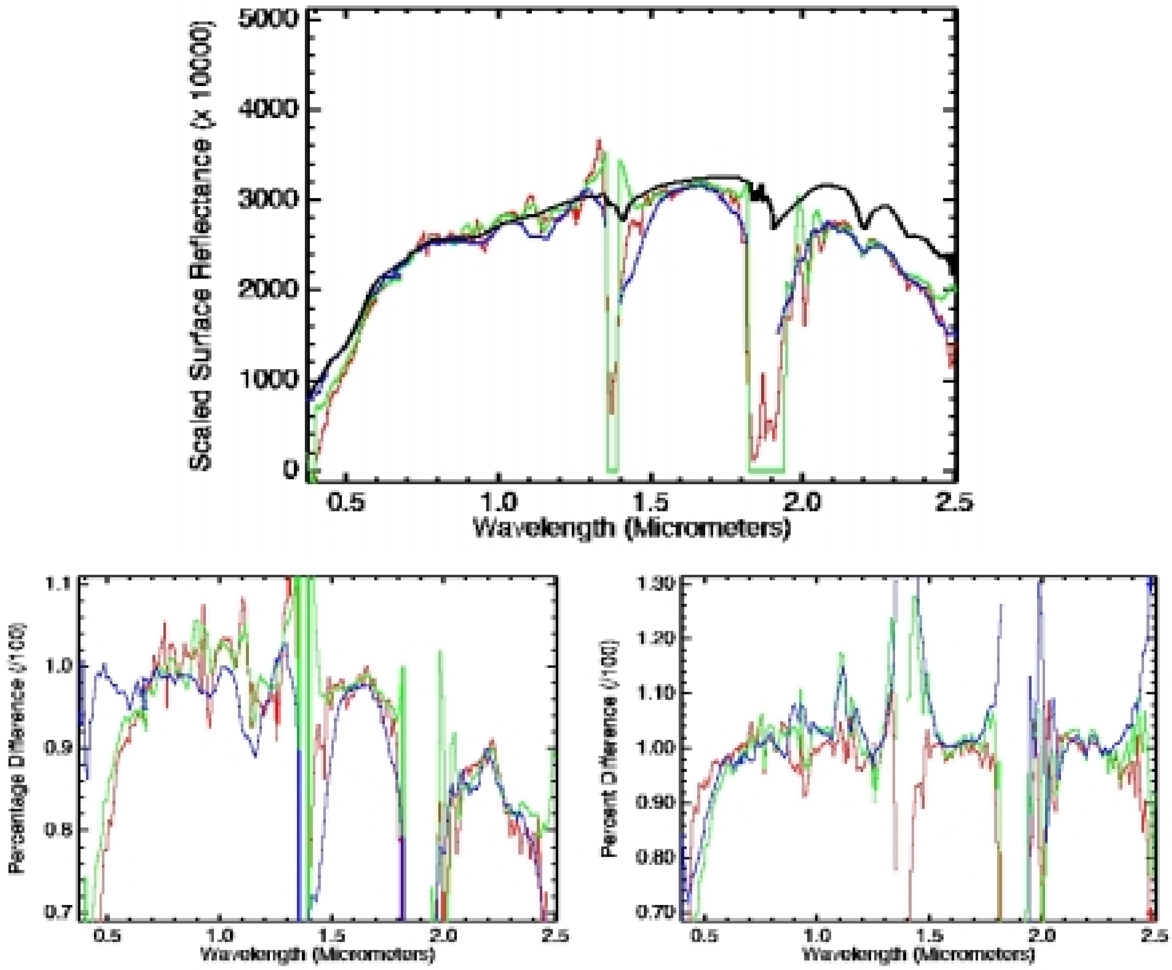


Figure 4: Comparison of Field, ATREM, ACORN, and FLAASH single-pixel spectra (with polish) for a typical Boulder, Colorado Gravel (Boulder Rifle Club Gravel #2). Top, field reflectance spectra and model-corrected image reflectance spectra (Field=black, ATREM=Red, ACORN=Green, FLAASH=Blue). Bottom-Left, ratios of image reflectance spectrum divided by field spectrum for the three atmospheric model corrections. Colors are the same as above. Note that image spectra generally match to within about +-5% absolute reflectance at most wavelengths, excluding atmospheric absorption bands (1.4 and 1.9 micrometers). Image spectra are significantly lower reflectance in the SWIR (2.0 – 2.5 Micrometer range) compared to the field spectrum. Bottom-Right plot shows comparison of ATREM/ACORN (Red), ATREM/FLAASH (Green), and ACORN/FLAASH (Blue). Comparison to each other indicates generally less than about 5% difference across most wavelengths. The worst matches are for the visible (0.4 -0.6 micrometers) and at wavelengths greater than about 2.3 micrometers.

4.5 Performance

One sub-objective of this work was to evaluate software performance for the three models tested. Table 1 compares the execution times for ATREM, ACORN, and FLAASH run with similar parameters, within the Environment for Visualizing Images (ENVI) software (Research Systems, 2003), producing similar products. Additional time is required to run various options for ACORN and FLAASH.

Table 1: Summary of execution times on 3.8m AVIRIS data (Line 9, Run 08 - 677 pixels x 3670 lines) rounded to the nearest minute. All methods were run on 3.4 Ghz Windows XP Workstation, 2Gb RAM.

Method	**Execution Time (Basic - No Polishing)**	**Execution Time (All Products and Polished)**
ATREM	4 min	14 Min[2]
ACORN	2 min	17 Min[3]
FLAASH	4 min[1]	16 Min[4]

1. Includes Adjacency Correction and Cloud mask
2. Includes manual EFFORT Polishing
3. Includes Visibility Estimate, Path Radiance in Water Vapor Fit, Liquid Water Fitting, Wavelength Matching, Noisy Channel Masking, and Automated Polishing
4. Includes Adjacency Correction, Cloud Mask, and Automated Polishing

5.0 Discussion and Conclusions

We applied model-based atmospheric correction algorithms to AVIRIS data to produce surface scaled reflectance for comparison of various atmospheric correction software results. Three atmospheric correction programs (ATREM, ACORN, and FLAASH) were evaluated using 3.8m spatial resolution AVIRIS data. ATREM uses a narrow band model to calculate atmospheric gas transmittance and models atmospheric scattering using a radiative transfer code (6S). Both ACORN and FLAASH utilize MODTRAN4 to estimate atmospheric parameters. All three methods also calculate water vapor on a per-pixel basis. Six different atmospheric correction results were calculated and compared. These included basic corrections and corrections with “polishing” – removal of artifacts. We found that all three models produce similar surface reflectance spectra when the same parameters are used, though some differences occur. Absolute reflectances for the 3.8m AVIRIS data were within about 5% of field spectral measurements acquired during the AVIRIS flight. Performance was considerably better at many wavelengths.

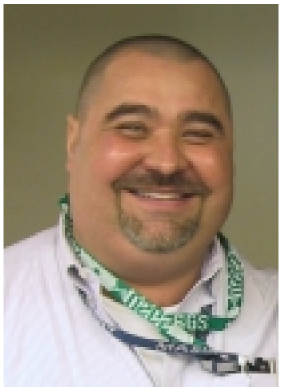
Other observations regarding the atmospheric model corrections and execution are as follows.

1. The water vapor images produced using all three methods similarly show that there is likely some band-to-band spatial misregistration for this AVIRIS dataset. Display of individual bands and animations have shown registration problems in AVIRIS bands 1-5 and 33-35.

2. A key feature of ACORN is full spectral fitting to solve for the overlap of absorptions between water vapor and liquid water in surface vegetation. Atmospheric corrections that do not include this feature tend to overestimate water vapor.
3. The FLAASH cloud mask applied to the Line 9, Run 8 AVIRIS data appears to map what are many obvious areas of bright, bare soils as “clouds”.
4. FLAASH requires temporary disk space on the order of 5x the size of the data file to be corrected. This can prohibit execution on large datasets (eg: the geocorrected 8Gb Line 10, R10 dataset required approximately 40Gb of disk space to execute, producing two 16Gb temporary files, followed by the 8Gb output file). The temporary files are deleted at the end of program execution, but even so, the full 40Gb were required to perform the FLAASH atmospheric correction. It appears that neither ATREM or ACORN produce similar temporary files, operating on a line-by-line basis and requiring only disk space for the output file.
5. ACORN and FLAASH execution times are dramatically affected by selecting all of the possible options. This time penalty makes it difficult to run the full ACORN/FLAASH implementations on larger datasets.
6. ACORN currently has an upper image size limit of 20,000 lines. Some of the geocorrected AVIRIS data had just over 20,000 image lines, thus the last few lines of these data could not be atmospherically corrected. It is actually preferable to run the atmospheric corrections on non-geocorrected data, so this limitation shouldn’t be a problem in most cases.
7. ACORN currently runs on PC’s only. FLAASH runs on PCs, UNIX, and LINUX. ATREM runs on both PC’s and UNIX, but is no longer being distributed.
8. ATREM has problems with long filename/directory paths and just doesn’t run – error messages are cryptic. ACORN has problems with very long file/directory names and sometimes needs to be run from a higher directory level.

In summary, ATREM, ACORN, and FLAASH produce comparable atmospheric correction results. ATREM provides a basic level of correction, however, is no longer being distributed. ACORN provides basic correction with enhancements for liquid water determination, some control over MODTRAN options, and additional multispectral correction capabilities. FLAASH provides basic corrections with enhanced corrections for adjacency effects and is most flexible for correction of hyperspectral data in light of available MODTRAN options.

6.0 Acknowledgements



Field spectral measurements were made with the assistance of K. Eric Live, U. S. Geological Survey.

The ACORN software was provided courtesy of ImSpec, LLC. The FLAASH software was provided by Research Systems, Inc.

This research is dedicated to the memory of Joseph M. Sadlik (1960 – 2003), a colleague and friend. Joe was instrumental in designing and initiating the Boulder hyperspectral project. His dedication to science and enthusiasm for life will not be forgotten.

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