# A comparison between six model-based methods to retrieve surface reflectance and water vapor content from hyperspectral data: A case study using synthetic AVIRIS data

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**Abstract**

**Six model-based methods, ACORN, ATREM, ATCOR4, CAM5S, FLAASH and HATCH, were used to retrieve reflectance information and water vapor content from synthetic AVIRIS data. The results were compared using objective method in four spectral segments across the sun radiation light. In the synthetic data, the highest spectral difference was found to be 26% and the lowest 1.1% in reflectance units as estimated from the Average Sum of Deviations Squared (ASDS) values. The reflectance-equivalent ASDS values were lower than the traditional max and min values, as ASDS averages reflectance in the spectral segment in question. Two kinds of reflectance retrieval difference were identified: 1) albedo drift and 2) spectral artifacts. Judging from the four selected spectral segments examined (VIS, NIR, SWIR-1, SWIR-2) a sequence that allocate the best method in each segment was established. It was recommended that for optimum atmospheric correction all methods are to be run and then a method for each pixel will be selected using look-up-table based on the surface basic coverage and the atmospheric condition.. A similar comparison was done with the retrieval of water vapor content by each of the six methods used. The water vapor content was found to be overestimated by ATREM (≈60%) and underestimated by HATCH (≈ 15%), whereas ACRON and ATCOR provided the most realistic results. It was found that the water vapor retrieval difference varies within the actual water vapor content and is significantly affected by the vegetation content, mainly because of the liquid water contribution. The prediction difference for the water vapor retrieval was found to have two sources: 1) liquid water occurrence and 2) miscalculation of the method used. It was concluded that the results of a model based correction technique, may vary both in retrieving reflectance values and water vapor content quite significantly from one method to another. This is true even when optimal conditions are used (zero spatial and spectral noise, no spectra line curvature ect.) and the environment signals are controlled. When adding other obstacles to the raw data (e.g. spectral and spatial noise, optical effects and more) more study has to be applied in order to pinpoint on the best method to be used. Although this study shows a methodology to judge method's performance to remove atmospheric attenuation, a separate study has to be applied in order to generate a similar look-up-tables per sensor and per mission.**

**Keyword list: Hyperspectral remote sensing, Atmospheric correction, AVIRIS**

## 1. INTRODUCTION

The retrieval of a continuous reflectance spectrum and water vapor content either from air or space platforms on a pixel by pixel basis, is the major advantage the hyperspectral (HSR, also known as Imaging Spectroscopy) technology provides. Accurate retrieval of reflectance information of the Earth surface is a key factor for conducting qualitative and quantitative remote sensing of both the Earth surface and atmosphere. Based on the Earth's thick atmosphere, significant absorption and scattering effects along the sun-surface-sensor pathway affect the retrieval of the absolute surface reflectance. Several model-based methods and strategies to correct the atmospheric effects and retrieve the water vapor content on a pixel by pixel basis are known and available commercially and scientifically (Mustard et al., 2001). The model-based methods are physically based codes, in which at sensor radiance is modeled using radiative transfer equations and data from detailed atmospheric and sun information archives (e.g., HITRAN database). Six model-based major methods are known in HSR practice: ATREM (Gao et al., 1993), ATCOR (Richter, 1996), ACRON (ACORN, 2001), FLAASH (Adler-Golden, 1998) CAM5S (O'Neil 1996), and HATCH (Qu et al., 2001) as well as their modifications, described by Sanders et al. (2001). The accessibility of model based methods in remote sensing packages, their short running time and friendly user interface, make them recently very popular and widely used by many users. However, as every model-based method relies on a different database and uses a different approach and different strategy to account for the atmospheric components (e.g. water vapor retrieval), differences in the final results may be expected. Needless to say, knowledge of the nature and magnitude of such variations are important for understanding and comparing the spatial, spectral and temporal hyperspectral results. Therefore, studies comparing the results of the atmospheric calibration methods have been published over the past decade (e.g.: Roberts et al., 1986, Farrand et al., 1994, Ben-Dor et al., 2002) orienting users to the drawbacks, limitations and advantages of each method. As most of comparison between methods were made on real data (e.g. Bosch and Alley, 1991), answer which method is adequate can not be obtained. This is because in real data, several effects are not set to be constant, not all pixels within the scene are examined and co registration of field and image pixels is problematic. This leads, most of the time to qualitatively rather than quantitatively based comparison. The purpose of this study is thus, to compare the above six methods under controlled (synthetic) environment simulating the AVIRIS sensor. AVIRIS is a JPL HSR sensor operates across the VIS-NIR-SWIR spectral region (0.4-2.5μm) and provides, today, the best HSR performances over all worldwide known HSR sensors. It consists of 224 channels with a 10nm FHMW and a pixel size ranging from 5m to 20 m (depending on the platform altitude). The comparison in this study is aimed at judging the methods' performances, objectively and quantitatively, at a very basic stage, retrieving both surface reflectance and water vapor content using all pixels in the scene. For that purpose we have generated a synthetic AVIRIS scene and have systematically and quantitatively examined each of the model based methods described above.

## 2. MATERIAL AND METHODS

2.1 **The retrieval methods used** The six selected methods for retrieving reflectance information and water vapor content from hyperspectral data are briefly described below: ATREM (*Atmospheric Removal Method;* Gao et al. 1993): HATCH *(High accuracy Atmospheric Correction for Hyperspectral; Qu et al., 2001*): ACRON(*Atmosphere CORrection Now; ACORN, 2002*): FLAASH (*Fast Line-of-sight Atmospheric Analysis of Spectral Hyper cubes Adler- Golden et al, 1998)* **A**TCOR-4 (*Atmospheric and Topographic CORrection* Richter and Schläpfer 2002) CAM5S (*Canadian Advanced Modified 5S, O'Neill et al, 1996)*

2.2. **Material** 2.2.1 **Synthetic AVIRIS Data** The synthetic area represents an authentic AVIRIS database (Green and Pavri, 2000) in term of geographic position and landscape (soil and vegetation and their mixture). The atmospheric radiative transfer code MODTRAN 4 (Berk et al., 1999) was used to create the atmosphere. The code was run 134 times, corresponding to 134 water vapor amounts ranging from a 0.5cm column to a 4.5cm column of water vapor. In order to generate the inputs for predicting the at-sensor radiance for each water vapor amount, the code was run three times with constant albedos of 0.0 (the path radiance term), 0.5 and 1.0cm. From these quantities, the two-way transmittance, path radiance, and spherical albedo were generated. With the addition of the surface reflectance and exoatmospheric solar spectrum, the at-sensor radiance can be predicted. The solar geometry was chosen to replicate an "average" imaging spectrometer data collection, run with a solar zenith angle of about 45deg. The MODTRAN model was set to "mid-latitude summer," a constant surface elevation (0 km), a visibility of 50 km, a sensor height of 100 km, and a $CO_2$ mixing ratio of 360ppm. The runs were performed with MODTRAN's two-stream DISORT and correlated-k algorithms. The surface spectral information for the input to the synthetic data sets was obtained from two field spectra of soil and vegetation acquired in Morgan County, Colorado that were convolved to an actual AVIRIS 2001 wavelength file (band centers and FHMW). The cube was constructed as follows: The 134 samples across the image were the 134 water vapor values; sample one contained a 0.5 cm column of water vapor, sample 134 contained 4.5 cm; the top line consisted of 100% vegetation, and the bottom line, 99% soil. The synthetic image was run by each selected method and the results were compared to the initial spectral information.

## 3. Results and Discussion

Figure 1(a,b,c) presents the "true" (input) abundance image of each component that used to generate the at-sensor radiance data (a–soil, b-vegetation, c-water vapor). Figure 1a shows the reflectance spectra of the endmembers' targets used to build the "surface" mixed image (soil and vegetation), while Figure 1b,c shows the radiance spectra of the endmembers (as a product of applying the atmosphere to the reflectance data) for two water vapor conditions: b -- low water (0.5cm) and c -- high water (4.5cm). As can be seen, the synthetic radiance spectra appear to satisfactorily represent real AVIRIS data, known from both practice and published literature (example: Green and Pavri, 2001). A noticeable spectral difference between the two water-level can be seen mainly around the water vapor absorption regions at 0.94, 1.14, and 1.34μm, going from low to high water vapor levels based on the water vapor level variations. The radiance data were then processed to retrieve the reflectance and water vapor content on a pixel by pixel basis. A discussion follows of the reflectance and water vapor retrieval performances spectrally.

3.1 **Reflectance retrieval**

Using the synthetic radiance data set for each of the six methods, new data cubes were generated. To judge the correction performance we selected 9 targets at different atmosphere and ground locations (4 pixel each) as follows: 100% vegetation (*n*1), 50% vegetation and 50% soil, (*n*2), and 100% soil (*n*3) across the low, medium and high water vapor conditions of (0.5(A*m*), 2.5(C*m*) and 4.5(E*m*) cm water vapor respectively. (*n* stands for the water vapor content and *m* for the vegetation fraction symbols for the selected targets). To objectively and quantitatively judge the performance of each selected methods to retrieve the reflectance values, we applied a ratio calculation technique in which a selected target is divided by its corresponding true (input) reflectance data and the deviation from a unity is then calculated and squared-sum across a selected wavelengths using Average Sum of Deviations Squared (ASDS) ( Ben-Dor et al. (2002) ).

Figures 2 plots the ratio spectra for target C2 (allocated in the center of the image and thus represents average ground and atmospheric conditions of the synthetic data (50% soil and 50% vegetation at 2.5 cm water vapor content zone). Figure 2a represent ATREM, HATCH and ATCOR and Figure 2b represents FLAASH, ATCOR and CAM5S. Omitting the strong abnormal features across the atmospheric absorption spectral zones (around 1.4μm and 1.9μm) and across the two spectral edges (at 0.45μm> and at 2.45μm< respectively), we divided the spectrum region into four main segments for further discussion as follows: VIS (0.45-0.7μm), NIR (0.7-1.3μm), SWIR-1 (1.52-1.75μm) and SWIR-2 (2.01-2.44μm).

Based on the above selected spectral segments, the ASDS values were calculated for every target for each spectral segment. In addition, a sum of all segments (ALL) was selected and its ASDS values were calculated to allow an overview of the entire spectral region. Doing so revel a performance sequence for each spectral segment and water vapor level. Based on this sequence we generated a look-up-table (Table 1) that provides the method in each spectral segment and water vapor condition (lowest ASDS values in each category)

| water content (cm) | coverage | 0.5 | 1.5 | 2.5 | 3.5 | 4.5 |
|---|---|---|---|---|---|---|
| ALL | vegetation | Acorn | Acorn | Acorn | CAM5S | Acorn |
| | vegetation -soil | Atcor | Atcor | Atcor | CAM5S | CAM5S |
| | soil | Atcor | Atcor | Atcor | Atcor | CAM5S |
| VIS | vegetation | Acorn | Acorn | Acorn | CAM5S | Acorn |
| | vegetation -soil | Atrem | Atrem | CAM5S | Atrem | Atrem |
| | soil | Atrem | Atrem | CAM5S | Atrem | Atrem |
| NIR | vegetation | Flaash | Flaash | Flaash | CAM5S | CAM5S |
| | vegetation -soil | Flaash | Flaash | Flaash | Atcor | Atcor |
| | soil | Atcor | Atcor | Atcor | Atcor | Atcor |
| SWIR-1 | vegetation | Atcor | Atcor | Atcor | Atcor | Atcor |
| | vegetation -soil | Atcor | Atcor | Atcor | Atcor | Atcor |
| | soil | Atcor | Atcor | Atcor | Atcor | Atrem |
| SWIR-2 | vegetation | Atcor | Atcor | Atcor | Atcor | CAM5S |
| | vegetation -soil | Atcor | Atcor | Atcor | Atcor | CAM5S |
| | soil | Atcor | Atcor | Atcor | Atcor | CAM5S |

From Table 1 it is postulated that HATCH method is missing from all of the presented categories while ATCOR performs in more than the 54%. ATCOR found in all categories but best performed in the SWIR-1 spectral region. CAM5S found to best performed at high water vapor content, occupies bout 40% of the 4.5cm water vapor content scenarios. ACRON found in 11% from the categories and best performs at vegetation targets under low and intermediate water vapor content. ATREM found in 11% of the entire categories and mostly in soil targets across the VIS region. FLAASH found to hold 8% of the cases mostly across the NIR spectral region and over vegetation areas. It can be concluded that there is no a single method that optimally performs across the entire spectral regions and thus a combination between available methods is required. In this regard we suggest to run automatically all six methods on a given data set and based on a look-up-table (similar to Table-1) to spectral mosaic the sixth cubes into a full corrected cube. The pre-classification process to select the targets in question (vegetation, soil or their mixtures) may be done via NDVI (or similar vegetation index) whereas water vapor level can be estimated in one of the methods suggested in the next section (for the entire scene).

3.2 **Water vapor retrieval**

3.2.1 **Synthetic data**

In each of the six methods, a complementary algorithm to retrieve the water vapor content, pixel by pixel, is available. In general, every method calculates the water vapor content differently and thus the final results may be different. To check the methods' performances in water vapor retrieval, a 2D scatter plot between the retrieved and true water vapor images in each scenario was constructed. These scatter plots, show significant linear relationships between most of the methods and the reference water vapor and their equations and R2 are provided in Table 2. Looking on these equations it is apparent that ATREM method overestimates the water vapor content by nearly 60%, whereas HATCH underestimates the water vapor content by about 15%, whereas ACRON and ATCOR provides relatively correct water vapor content. In general, variation of the points in the scatter plot from a perfect 1:1 line may be a product of two sources: 1) existence of another chromophore in the pixel's spectrum (e.g. liquid water) which makes the absorption feature around the relevant region a mixed problem; and 2) a problem in the algorithm calculating the water vapor content. Table 2 provides the linear equation obtained from the scatter plots for each soil coverage, in the six methods examined. Variation from 1:1 line in vegetation account for sources 1+2 and variation in soil account for source 2. Differences between the two (vegetation and soil) provides source's 1 effect.

| **Surface Converge METHOD** | **Vegetation** | **Vegetation + Soil** | **Soil** |
|---|---|---|---|
| **HATCH** | 0.874X +0.1672 (R2=0.998) | 0.842X+0.1575 (R2=0.998) | 0.8346X+0.1104 (R2=0.998) |
| **ACRON** | 1.024X-0.0021 (R2=1) | 1.027X-0.0063 (R2=1) | 1.026X-0.0048 (R2=0.999) |
| **ATREM** | 1.657X-0.1319 (R2=0.999) | 1.611X-0.167 (R2=0.999) | 1.539X-0.219 (R2=0.998) |
| **ATCOR** | 1.057X-0.0132 (R2=0.994) | 1.0488X-0.037 (R2=0.995) | 1.044X-0.0439 (R2=0.997) |
| **CAM5S** | 1.144X-0.6225 (R2=1) | 1.142X-0.620 (R2=1) | 1.139X-0.619 (R2=1) |
| **FLAASH** | 0.677X+3.753 (R2=0.8539) | 0.702X+3.694 (R2=0.861) | 0.701X+3.692 (R2=0.996) |

As can be seen from the linear equations presented in Table 2, vegetation areas overestimate water vapor in HATCH, ATREM, CAM5S and ATCOR whereas in ACORN and FLASSH vegetation has no significant change. The best fit to 1:1 was obtained in ACRON and ATCOR in all targets. ATREM overestimate water vapor by nearly 60% and CAM5S by 14% where HATACH underestimate it by nearly 13%. The worst method to retrieve water vapor is found to be FLAASH with 30% underestimating of the water vapor content with relatively poor regression level. Based on the above results, we can set a sequence to select the best method for water vapor content retrieval as follow: ACORN=ATCOR > HATCH> CAM5S>ATREM> >> FLAASH.

## 4. SUMMARY AND CONCLUSIONS

Model-based methods to retrieve surface reflectance and water vapor content give varied results. Variation can be seen in each method when surface reflectance is changing (from pure vegetation to pure soil), when the water vapor is constant and when it is changing (from 0.5cm to 4.5cm), while the surface reflectance is constant. The synthetic data provide optimal conditions for reliable comparison and judgment between the basic performances of the three selected methods. Differences of more than 26% between actual and retrieved reflectance were found in particular wavelengths. Two sources of difference in retrieving reflectance were found: albedo drift and artifacts. A statistical parameter to quantitatively calculate the total difference in selected spectrum segments was used to establish a look up table to select a method for a pixel for the atmospheric correction. CAM5S was found to better perform in relatively humid areas whereas ATCOR in more than 50% of the scenarios (data coverage and water vapor content). In generation of the water vapor image, ATREM has been found to overestimate water vapor by about 60%, HATCH to underestimate it by about 15% and ACRON and ATCOR to provide reliable results with a low variation of about 1%. FLAASH was found to provide worst results. Vegetation coverage adds liquid water signals to the calculated water vapor content. In summary it can be concluded that every model-based method has its own drawbacks and limitations whereas the synthetic data generator along with the ASDS calculation provide a reliable tool to examine their performances. Although we believe that the conclusions of this paper may be valid for other 2001 AVIRIS data sets, with similar reflectance properties, other sensors and other targets require a separate investigation of their performances in both water vapor and reflectance retrieval. For future comparison of similar questions, the ASDS parameters and the spectral segments used in this study are highly recommended.

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