Retrieval of the Horizontal and the Vertical Water Vapor Distribution from AVIRIS Data

Daniel Schläpfer, Klaus I. Itten
Remote Sensing Laboratories (RSL), Department of Geography, University of Zurich, CH-8057 Zurich, Switzerland
Phone: +41 1 257 51 45, Fax: +41 1 362 52 27, E-mail: dschlapf@geo.unizh.ch

Johannes Keller
Paul Scherrer Institute (PSI), CH-5232 Villigen PSI, Switzerland
Phone: +41 56 310 20 65, Fax: +41 56 310 45 25, E-mail: johannes.keller@psi.ch

ABSTRACT: The relationship between geocoding and hyperspectral atmospheric image processing is shown based on tropospheric water vapor contents. An advanced geocoding procedure and a new water vapor retrieval technique is applied to AVIRIS data. Terrain modelling techniques allow the combination of digital elevation model data and geocoded water vapor distribution images. Possibilities are shown, how to calculate columnar profiles as well as how to derive the concentration of water vapor along terrain slopes. Furthermore, images of the terrain independent relative humidity distribution are processed. The resulting images and profiles agree satisfyingly with in situ measurements and have the potential to provide new information about water vapor distribution in the atmosphere.

1. INTRODUCTION

Water vapor is an atmospheric component of major interest in meteorologic and climatologic sciences. Its measurement is a crucial factor for the input into many atmospheric models as well as for radiative transfer calculations in remote sensing. The retrieval of atmospheric water vapor using imaging spectrometry has been vastly improved during the last years. The new algorithms show satisfying results over flat terrain with high surface albedo variations. However, the problem, how to quantify the columnar contents in mountainous areas was still unsolved. Using Digital Elevation Models (DEM) is one of the possibilities to introduce terrain parameters. Other image based methods, like using the well mixed oxygen or carbon dioxide contents to obtain the terrain information are not mature yet. The two ways to use the DEM together with the image data is to project the image on the cartographic geometry or to transform the DEM to image geometry. The first approach was chosen for this study.

2. PARAMETRIC GEOCODING

Nearly all current imaging spectrometry data is obtained by scanning airborne systems. So does the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS; Vane 1988) carried by an ER-2 aircraft at 20 km height a.s.l. The position of such instruments never is as stable as on spaceborne platforms. Therefore, geometric distortions occur due to variations of the flightline as well as to the attitude (given by roll, pitch and yaw angles) of the plane. These distortions can not be corrected by ground control point based traditional georeferencing procedures, since they usually are based on polynomial transformations of the image.

2.1 *The PARGE Algorithm*

The used georeferencing procedure is based on a parametric approach and allows sub-pixel accuracy even in steep terrain. A predecessor of the algorithm was developed by Meyer (1994). The new PARGE (parametric geocoding) algorithm involves the following features:

- consideration of the exact navigation data by line or by pixel
- correction of roll, pitch and yaw at small roll/pitch values
- consistent data structure for various airborne imaging instruments
- ground control point based algorithms for auxiliary data offsets estimation
- output to original DEM geometry
- two geocoding algorithms for different accuracy requirements are implemented:

1st: sub-pixel accuracy is achieved by DEM-oversampling algorithm
2nd: pixel accuracy is reached in another fast, pixel centre based algorithm

- nearest neighbour techniques prevent data modifications
- fully IDL (Interactive Data Language, RSI Inc.) based application with window based user interface

2.2 *Geocoding of AVIRIS Data*

The algorithm was applied to AVIRIS 1991 and 1995 data over complex terrain in Central Switzerland and in California, respectively. The results for the 1991 data sets are described in Meyer (1993). The 1995 data set was flown west-east oriented, this in contrast to the 1991 data, which was flown from north to south. These differences together with the differing cartographic representation between Northern American and Swiss coordinate systems were the reasons, why we decided to write the location-, platform- and flight-direction independent new PARGE algorithm.

The internal navigation system of the airplane provided only poor resolution at low absolute accuracy, since there was no differential GPS system mounted during the 1995 AVIRIS campaign. Therefore, it was necessary to reconstruct the flightline from the image data, using ground control points and assuming a straight flight track. This assumptions leads to a lower accuracy of the geocoding than potentially possible. On the other hand, the faster pixel centre based algorithm could be used and performed the geocoding of the image to 30 m DEM resolution within half an hour on a Sun SPARC 20 machine. The geocoded image is shown in figure 1 in comparison with a DEM shadow view image. Ridge lines of the mountains fit within one pixel shift.

Figure 1: Geometric corrected image Camarillo 1995 in comparison with the digital elevation model in shadow view mode

3. ATMOSPHERIC PRE-CORRECTED WATER VAPOR RETRIEVAL

A columnar water vapor retrieval method using imaging spectrometry data has been developed in the last years (Green 1989, Bruegge 1990, Gao 1990, Schläpfer 1995/1997). The so called atmospheric pre-corrected differential absorption (APDA) technique involves a terrain dependent correction of the atmospheric path radiance term before the apparent transmittance values are converted to total columnar water vapor amounts. The MODTRAN3 radiative transfer code (Kneysis 1995, Berk 1989) is used to calculate the spectral path radiance and to tune the conversion function for the atmospheric conditions of a specific scene. The DEM of the geocoded scene allows to perform a height dependent atmospheric pre-correction before the differential absorption technique is applied. The APDA technique reduces the errors due to background reflectance variations significantly compared to classical differential absorption techniques and decreases the systematic error in absolute water vapor retrieval as well (Borel 1996). The apparent transmittance T is approximately given by the APDA ratio number R_{APDA} (Schläpfer 1997):

$$T_{H_2O} \approx R_{APDA} = \frac{\overline{[L_m - L_{atm,m}]_i}}{LIR([\lambda_r]_j, [L_r - L_{atm,m}]_j)\big|_{\overline{(\lambda_m)_i}}} \qquad (1)$$

L_m is the radiance values at the sensor in measurement channels within the 940nm water vapor absorption band and L_r in the reference channels, aside of the feature. A set of i measurement channels and j reference channels is defined prior to the ratioing (Schläpfer, 1995). The function $LIR([\lambda_r], [L_r])$ de-

Figure 2: Columnar water vapor profile retrieval using geocoded imagery and a digital elevation model

scribes a linear regression line through a number of reference channels, evaluated at the centre wavelengths λ_m of the measurement area within the absorption band. L_{atm} is the atmospheric path radiance not reflected by the ground in the used channels (*i,j*). The transmittance values are transformed to total columnar water vapor (precipitable water) *PW* using an exponential relationship (Schläpfer, 1996):

$$PW = -\left(\frac{\ln(R_{APDA}) + \gamma}{\alpha}\right)^{\frac{1}{\beta}} \quad (2)$$

where α, β and γ are empirical constants retrieved from MODTRAN simulations at known water contents over an averaged vegetation spectrum.

4. WATER VAPOR PROFILE CALCULATION ALONG TERRAIN SLOPES

4.1 *Columnar Water Vapor Profile Retrieval*

In mountainous areas it is not possible to interpret the spatial water vapor distribution satisfyingly, since the columnar water vapor diminution by hills overrides the spatial information. A technique was found to solve this problem: The columnar water vapor is averaged at a number of discrete height levels of the digital terrain model to obtain a mean columnar water vapor profile $PW_p(h)$ within the image.

$$PW_p(h) = \overline{PW(x, y, h_{x,y})} \quad (3)$$

$$\text{with:} \quad h - \frac{\Delta h_p}{2} \le h_{x,y} \le h + \frac{\Delta h_p}{2}$$

where Δh_p is the resolution of the columnar profile retrieval and h denotes the height level. $PW(x, y, h_{x,y})$ is the previously retrieved columnar water vapor at the coordinates (*x,y*). The corresponding height $h_{x,y}$ per data point is read directly from the DEM and introduced into equation (3).

Figure 2 shows an example of columnar water vapor profiling for 1991 AVIRIS data. A fairly steep slope up to the Zugerberg mountain could be used for

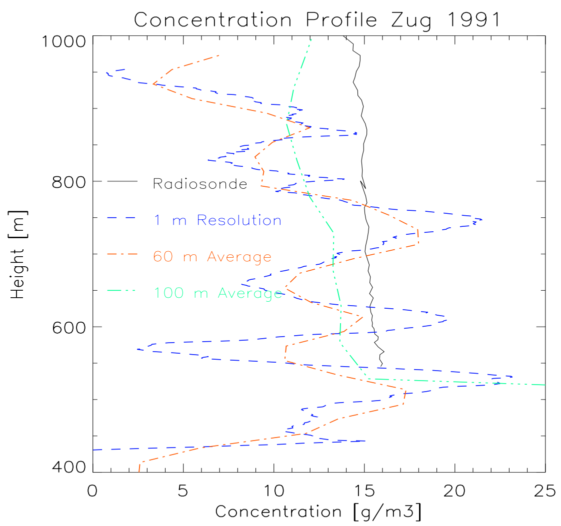

Figure 3: Variations of the concentration profile at varying resolution in comparison with a radiosonde profile.

the calculation. The lake area has to be masked because it is still not possible to get the water vapor over water with a satisfying accuracy. A kind of noise appears in the calculated profile with height, since it was derived at lowest 1m resolution. A low number of piexels per height level and the non-smoothed 1991 data quality are the reasons for this shape. Already a resolution of 20m improves the columnar profile appearance significantly and was chosen for the further calculations.

4.2 *Concentration Profiles Retrieval*

Water vapor concentration profiles along terrain slopes are determined from total columnar water vapor contents by calculating the variation of the columnar water vapor with height. A floating regression line through a number of columnar data points is calculated. Its resolution is given by the height difference Δh_u between the to limits of the regression line. The slope of the line denotes the water vapor concentration u at the height level h:

$$u(h) = \frac{PW_p\left(h - \frac{\Delta h_u}{2}\right) - PW_p\left(h + \frac{\Delta h_u}{2}\right)}{\Delta h_u} \qquad (4)$$

The retrieved profiles within one specific image vary depending on the vertical resolution (see figure 3): High erroneous variations are reported at vertical resolutions from 1 to 10 meters. At 20 to 50 meters there are still height dependent variations, which are not reported from the radiosonde profiles. At 100 m and lower resolution the profile is similar to

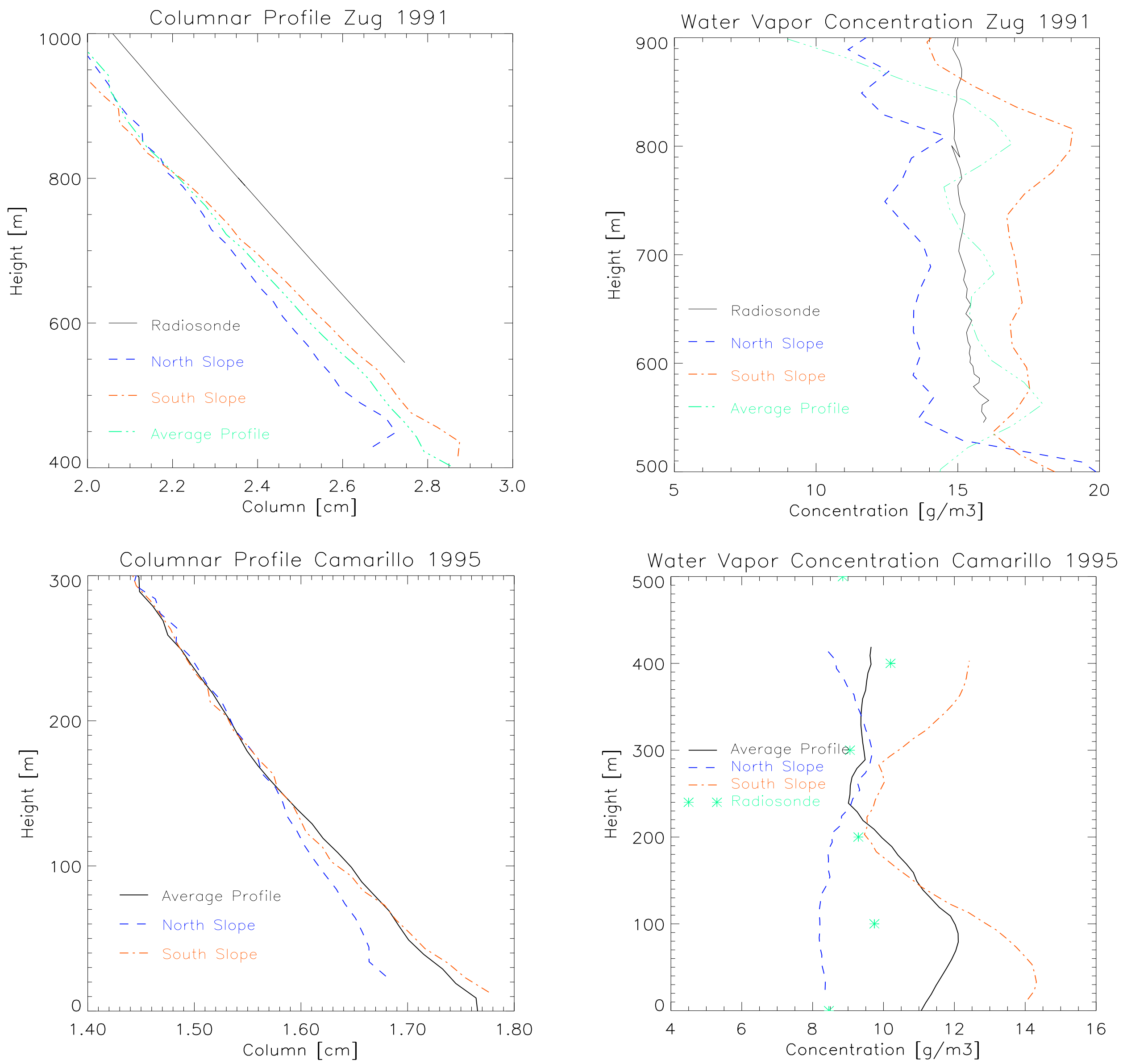

Figure 4: Columnar and concentration water vapor profiles retrieved from AVIRIS 1991 and 1995 data

the radiosonde measurements.

Not all terrain is suited for this kind of profile processing: There must be height variations from 200 meters up within the area. This range is based on the limited resolution of profile retrieval. Furthermore, the region of interest shall not be larger than 5 to 10 square kilometers since otherwise a mixture of horizontal distribution and vertical profile within the atmosphere occurs. Thus, the best results can be achieved along steep homogenously increasing mountain slopes.

4.3 *Comparison of North and South Slope Profiles*

The above methodology is applied to AVIRIS data over complex terrain in Central Switzerland and in California. For both processed images (AVIRIS "Zug", 1991 and "Camarillo", 1995) the columnar and the concentration profiles were retrieved over one specific mountain. In 1991 the radiosonde profile was taken within the image area at the time of the overflight.The 1995 sounding originates from a measurement one day before close to the scene, at a similar meteorological situation.

Figure 4 shows, that the columnar profiles differ mostly in the lowest part of the mountains and agree at the top. They are underestimated relative to radiosonde measurements by about 5% for the 1991 data and by more than 10% for 1995 data We suppose that the worse result in the Californian scene is based on the non-simultaneous radiosonde data. Obviously, there were much higher water vapor concentrations in the upper boundary layer, when the sonde was launched. The concentration profiles for 1995 agree within a 10% range, depending strongly on the aspect of the slope. The south slope of the mountain shows higher concentration than the north side. This can be explained by higher convection streams on the warmer side advecting humid surface air.

Similar results were achieved for 1991 data. A good agreement between radiosonde and AVIRIS calculated concentration profiles was found within a range of ±7%. It is still to be investigated, whether the variations with height are real signals of water vapor disturbances on the slope or if they occur terrain dependent from horizontal variations (e.g. on inhomogenous steepness of the slope).

5. REDUCTION OF TERRAIN INFLUENCE

In mountainous areas it is not possible to interpret the spatial water vapor distribution satisfyingly since the columnar water vapor diminution by hills overrides the spatial information. The columnar profiles combined with DEM-height information can be used to reduce the water vapor information to a flat scene. An artificial average water vapor column image is produced mapping the (already averaged) columnar profile information PW_p back to the DEM by assigning each height level of the DEM *h(x,y)* the corresponding averaged columnar profile value. This idealized water vapor image is subtracted from the originally calculated water vapor distribution *PW(x,y)*, which yields a map of the relative water vapor distribution $PW_{rel}(x, y)$ (see figure 5):

$$PW_{rel}(x, y) = PW(x, y) - PW_p(h(x, y)) \qquad (5)$$

with PW_p values derived from equation (3). The topographic influence now is minimized and the higher water vapor concentrations on southern slopes appear clearly in the image (see also figure 7).

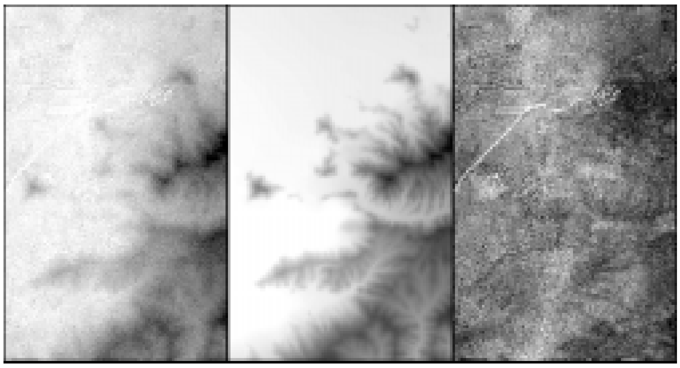

Figure 5: Retrieval of terrain adjusted water vapor: The ideal averaged water vapor (middle) is subtracted from the calculated water vapor (left) to obtain a relative water vapor image (right)

5.1 *Influence of Geocoding on Terrain Adjustment*

Geocoding is a indispensable task for atmospheric processing of imaging spectrometer data. The thickness of the atmosphere is dependent on the height of the terrain and therefore can be calculated from the digital elevation model (DEM). This parameter can only be linked to image data, when they are geocoded precisely to DEM geometry. This link is used for atmospheric correction algorithms as well as for the algorithms described in this paper. Figure 6 shows the sensitivity of the terrain adjustment procedure to a geometric shift. A inaccuracy of about 3 Pixels (here: 90 m) makes the procedure useless over the mountain area.

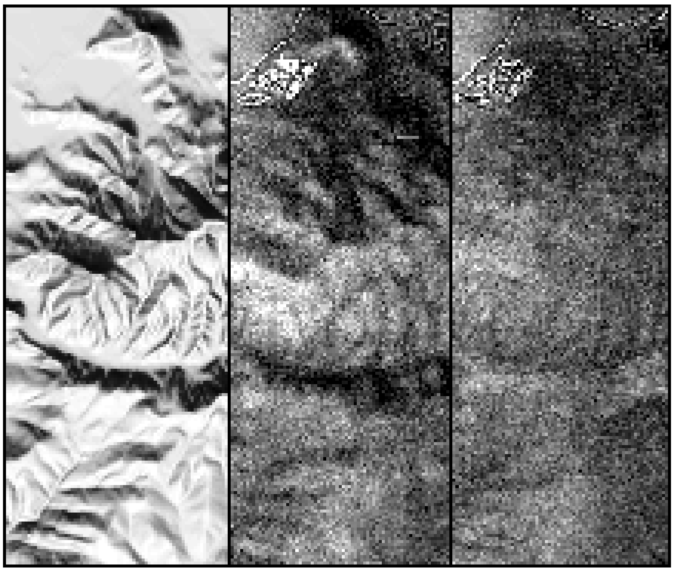

Figure 6: Influence of the geocoding algorithm accuracy on relative trace gas retrieval: Left: DEM shadow view; middle: Geocoding with up to 3 Pixels shift; right: Geocoding as good as possible (up to 1 Pixel shift)

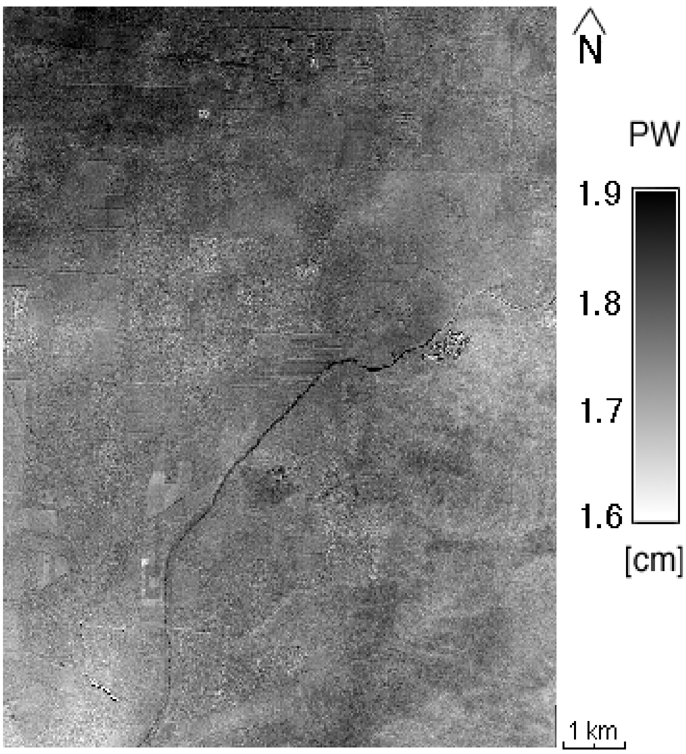

Figure 7: Terrain adjutive water vapor calculated from the AVIRIS 95 scene Camarillo, the values were enhanced by an average of 1.75 cm to obtain a sea level reduced columnar water vapor distribution map.

5.2 *Result*

The relative water vapor is given now as negative and positive difference values independent on the terrain (figure 7). It is possible, to obtain again columnar images by adding the average of the lowest height levels water vapor column. For the Camarillo data a value of 1.75 cm was added. The new kind of image allows a real horizontal distribution interpretation. Higher amounts over the south slopes of the mountains or in specific valleys help to understand small scale convections and clean air coming from the sea in the south appears as wide spread feature within the image.

6. CONCLUSIONS

The developed processing chain to retrieve water vapor from AVIRIS data consists now of the following steps: First, the raw image is geocoded to a DEM geometry (this step may be skipped over completely flat terrain). Second the columnar water vapor is retrieved from the image. Then, columnar profiles can be calculated depending on height, and the terrain adjustment can be performed. Last, it is possible to calculate specific concentration profiles along terrain slopes.

Imaging spectrometry is shown to have the potential of providing new information about tropospheric gas distribution. The new processing techniques, using the digital elevation model together with the georeferenced water vapor images, allow the quantification of horizontal distributions at a high resolution of about 20 meter and the estimation of vertical concentration profiles at resolutions down to 100 m. The technique allows to gather important information about low tropospheric water vapor concentrations and could help to improve and test evapotranspiration models. Air transport processes and pollution modelling in alpine valleys could be another application of the method

As a next step, the PARGE geocoding and the APDA algorithm will be improved to an operational state. The testing will be based on scenes from various instruments. The results of terrain adjustment might be a quality assessment step for the algorithms, since irrealistic water vapor distributions indicate problems within the processing chain.

7. ACKNOWLEDGEMENTS

The Swiss National Science Foundation and the Paul Scherrer Institute (PSI) are greatly acknowledged for the support of this study. Special thanks goes also to C. Borel (Los Alamos National Laboratory), for support in developing the APDA technique and to P. Meyer for essential inputs to the PARGE application.

8. REFERENCES

Berk, A. Bernsten L.S., Robertson D.C. 1989: *A Moderate Resolution Model for LOWTRAN7*. Air Force Geophysics Laboratory, Hanscom AFB, MA

Borel C.C., and Schläpfer D. 1996, *Atmospheric Pre-Corrected Differential Absorption Technique to Retrieve Columnar Water Vapor: Theory and Simulations*. Summaries of the Sixth Annual JPL Airborne Science Workshop, Vol.1, Green (ed.), JPL Pasadena CA, USA, p 9

Bruegge C.J., Conel J.E., Margolis J.S., Green R.O., Toon, G., Carrère, V., Holm, R.G., Hoover, G., 1990: *In-situ Atmospheric Water-Vapor Retrieval in Support of AVIRIS Validation*. SPIE Vol. 1298 Imaging Spectroscopy of the Terrestrial Environment, pp 150 - 163

Gao, B.-C., Goetz, A.F.H., 1990: *Determination of Total Column Water Vapor in the Atmosphere at High Spatial Resolution from AVIRIS Data Using Spectral Curve Fitting and Band Ratioing Techniques*. SPIE Vol. 1298, Imaging Spectroscopy of the Terrestrial Environment, pp 138 - 149

Green, R.O., Carrère, V., Conel, J.E., 1989: *Measurement of Atmospheric Water Vapor Using the Airborne Visible/Infrared Imaging Spectrometer*. Proceedings Workshop Image Processing, Am. Society Photogrammetry and Remote Sensing, Sparkes, NE, pp 31 - 43

Kneisys F.X., Abreu L.W., Anderson G.P., Chetwynd J.H., Shettle E.P., Berk A., et al., 1995: *The MODTRAN 2/3 and LOWTRAN Model*. Abreu L.W. and Anderson G.P. (ed.), Appendix C, Ontar Corporation, North Andover, MA, p 267

Meyer, P, 1994, *A parametric approach for the Geocoding of Airborne visible/infrared Imaging Spectrometer (AVIRIS) Data in rugged terrain*, Remote Sensing of Environment, Vol. 49, Nr. 2, pp 118-130

Schläpfer, D., J. Keller, 1995, *Imaging Spectrometry of Tropospheric Ozone and Water Vapor: Evaluation of Methods*, Proc. of the 15th EARSeL Symposium Basel, Balkema, Rotterdam, pp 439 - 446

Schläpfer D., Borel C.C., Keller J., and Itten K.I., 1996, *Atmospheric Pre-Corrected Differential Absorption Technique to Retrieve Columnar Water Vapor: Application to AVIRIS 91/95 Data*. Summaries of the Sixth Annual JPL Airborne Science Workshop, Vol.1, Green (ed.), JPL Pasadena CA, USA, p 9

Schläpfer D., Borel C.C., Keller J., and Itten K.I. 1997: *Atmospheric Pre-Corrected Differential Absorption Technique to Retrieve Columnar Water Vapor*. submitted to International Journal on Remote Sensing of the Environment, p 33

Vane G., Goetz A.F.H., 1988: *Terrestrial Imaging Spectroscopy*. Remote Sensing of Environment, Nr. 24, Elsevier Science Publishing Co., Inc., New York, pp 1-29

FrameMaker has detected one or more PostScript errors in this document. (dschlapf) Please check your output.