# IMAGING SPECTROMETRY OF TROPOSPHERIC OZONE AND WATER VAPOR

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ABSTRACT: Imaging spectrometry has the potential of remotely detecting atmospheric trace gases on the basis of their absorption of radiation. Ozone absorbs particulary in the ultraviolet and visible range of the spectrum, whereas water vapor has strong absorption features in the near infrared. Hence, spectrometry is expected to be a promising tool to extract these trace gas contents in a given air column by using the correlation between cumulative trace gas amount and absorption strength in the sensor channels located in the absorption bands. New mathematical methods of channel selection and method evaluation for measuring atmospheric trace gases are presented. Three already known and four new differential absorption techniques are evaluated by using MODTRAN2 simulations of the radiance spectrum at the sensor level and an analytical error propagation analysis. Finally, the best methods and channel combinations are selected and applied to AVIRIS data of Central Switzerland. The spatial ozone distribution could be estimated over water in a qualitative manner, whereas the total column water vapor content could be quantified over land with an accuracy of about ±6%.

## 1 INTRODUCTION

During the AVIRISwiss / MAC Europe experiment in July 1991, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) onboard a NASA ER-2 aircraft was flown over Central Switzerland (Schaepman, 1992). The AVIRIS is sensitive in 224 channels located between 400 and 2455 nm with a resolution of 10 nm. At the same time, additional ground-based and airborne measurements of meteorological parameters and trace gas concentrations were taken within the framework of the Swiss field experiment POLLUMET (Neininger, 1991). Based on this data, investigations to detect atmospheric trace gases by means of imaging spectrometry were initiated.

Since experiments with controlled trace gas variations can not be performed directly, calculations with radiative transfer codes (RTC) have to simulate the influence of a specific trace gas on the radiance at the sensor level. In this study the spectral transmittance and radiance are calculated by MODTRAN2 simulations (Berk, 1989).

The optical measurement of atmospheric trace gases can be performed using sensor channels located in bands or lines of the absorption spectrum. To quantify the trace gas amount, the so called differential absorption technique is applied (Carrère, 1993; Kaufmann, 1992). It performs a ratioing between influenced channels within the absorption band (*measurement channels*) to non influenced channels besides the band (*reference channels*). Measurement channels are ideally sensitive to the trace gas of interest and as insensitive as possible to noise and other disturbing effects. Reference channels are located as close as possible to measurement channels, but may not be influenced by any absorbing gases. The various ratioing methods differ from one another by the number of selected channels and by the calculation technique.

The objective of this work is to find the best performing differential absorption technique for imaging spectrometry of tropospheric ozone and water vapor.

## 2 METHODOLOGY OF CHANNEL SELECTION

### 2.1 *Selection of the measurement channels*

Measurement channels must meet three conditions:

a) They must be sensitive to variations of the trace gas amount:

→ *Sensitivity*

b) The difference between the signal of the trace gas and the noise must be clearly discernible:

→ *Significance*

c) Other absorbing atmospheric species must not disturb the signal of the trace gas of interest:
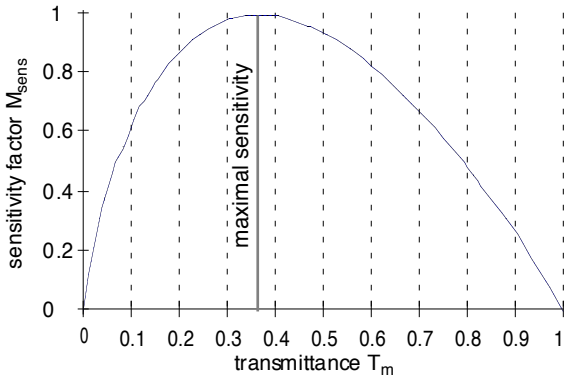
→ *Cross Sensitivity*

fig. 1: Sensitivity factor Msens as a function of transmittance Tm

a) *Sensitivity*

An absorptance band has a similar behaviour to the trace gas concentration as a single line. Hence the Beer-Lambert law is a reasonable description of the transmittance function:

$$T_m = e^{-k_m \cdot u_m} \qquad (1)$$

The change of the transmittance $T_m$ due to a variation of the total column $u_m$ of the trace gas $m$ follows directly as

$$\frac{\partial T_m}{\partial u_m} = -k_m T_m = \frac{\ln T_m}{u_m} \cdot T_m \qquad (2)$$

where $k_m$ is the absorption coefficient dependent on the wavelength. Equation (2) has its maximum at $T_m = 1/e$ independent on the absorption coefficient. The sensitivity factor $M_{sens}$ is defined as equation (2) normalised to a maximum value of 1 (see fig. 1):

$$M_{sens} = -e \cdot \ln T_m \cdot T_m \qquad (3)$$

b) *Significance*

The significance factor $M_{sign}$ is defined as

$$M_{sign} = \frac{(L_{A,m} - L_S) - \Delta L_S}{L_{A,m} - L_S} = 1 - \frac{\Delta L_S}{L_{A,m} - L_S} \qquad (4)$$
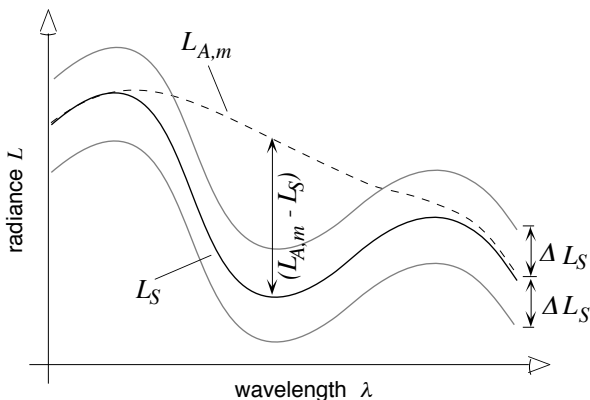


fig. 2: Significance of an absorption feature to total noise

where $L_S$ is the radiance at the sensor level and $L_{A,m}$ is the theoretical radiance if the trace gas amount were zero. $\Delta L_S$ is the effective noise due to the noise equivalent radiance of the sensor ($L_{NER}$) and to the uncertainty $\Delta\rho$ of the ground reflectance $\rho$:

$$\Delta L_S = \sqrt{(L_{NER})^2 + \left(\frac{\Delta\rho}{\rho} \cdot L_{S,dir}\right)^2} \qquad (5)$$

$L_{S,dir}$ is that part of $L_S$ which is reflected by the ground and directly transmitted to the sensor.

c) *Cross sensitivity:*

The factor $M_{cross}$ takes into account the influence of any disturbing gases $a$::

$$M_{cross} = \prod_a (T_a) \qquad (6)$$

The three effects described in the equations (3), (4) and (6) are now combined to obtain the channel qualifier $M_{meas}$ for the measurement channels:

$$M_{meas} = M_{sens} \cdot M_{sign} \cdot M_{cross} \qquad (7)$$

2.2 *Selection of the reference channels*

A reference channel has to meet the following conditions:

a) The signal should not be influenced by any atmospheric species.
  → *Transmittance*

b) Its effective signal to noise ratio must be as big as possible.
  → *Noise*

a) *Transmittance*

The transmittance factor $M_{trans}$ originates from a multiplication of the transmittance factors of all absorbing gases:

$$M_{trans} = T_m \cdot \prod_a (T_a) \qquad (8)$$

b) *Noise:*

Similar to the significance factor, $M_{sign}$ the noise factor $M_{noise}$ is based on the effective noise at the sensor:

$$M_{noise} = 1 - \frac{1}{L_S}\sqrt{(L_{NER})^2 + \left(\frac{\Delta\rho}{\rho} \cdot L_{S,dir}\right)^2} \qquad (9)$$

Analogous to (7) the measures (8) and (9) are multiplied to evaluate the reference channels:

$$M_{ref} = M_{trans} \cdot M_{noise} \qquad (10)$$

# 3 EVALUATION OF VARIOUS DIFFERENTIAL ABSORPTION TECHNIQUES

## 3.1 *Compilation of the techniques*

Differential absorption techniques are a practicable way to determine trace gas contents from a spectrum of an absorption band. For their implementation different combinations of channel sets out of the selected reference and measurement channels are used. In the following section a collection of already known and some new techniques are described.

### a) *Single band ratio (SBR)*

The single band ratio (SBR) quotient is defined by the ratio value $R_{SBR}$ of one measurement to one reference channel (Kaufmann, 1992):

$$R_{SBR} = L_m / L_r \qquad (11)$$

It is the prototyp of the differential absorption techniques. The term 'channel' stands for the radiance values $L_m$ and $L_r$ respectively, which are the radiance values measured in one measurement and one reference AVIRIS channel respectively. The SBR technique is simple in implementation but very sensitive to varying background characteristics, because the slope of the reflectance spectrum is not considered.

### b) *Continuum interpolated band ratio (CIBR, see fig. 3)*

The reflectance slope can be considered by using two reference channels on both sides of the absorptance band. One measurement channel is ratioed to a linear interpolation between two reference channels at the same wavelength (Bruegge, 1990).

$$R_{CIBR} = \frac{L_m \cdot \left( \lambda_{r2} - \lambda_{r2} \right)}{L_{r1} \cdot \left( \lambda_{r2} - \lambda_m \right) + L_{r2} \cdot \left( \lambda_m - \lambda_{r1} \right)} \qquad (12)$$

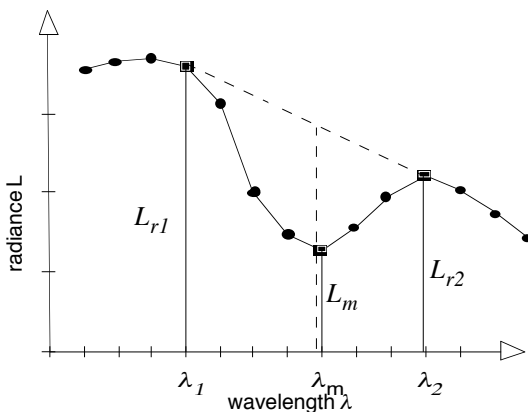where $L_m$ is the radiance at the measurement channel with its central wavelength $\lambda_m$ and $L_{r1}, L_{r2}$ are the radiances at the reference channels at the central wavelengths $\lambda_{r1}, \lambda_{r2}$.

### c) *Quadratic interpolated band ratio (QIBR)*

The principle of the CIBR can be extended by adding a third reference channel. The linear interpolation is replaced by a square function through the three points. In that way the shape of the ground reflectance is supposed to be of second order. The ratio number is defined as (Schläpfer, 1994):

$$R_{CIBR} = \frac{L_m}{a \cdot \lambda_m^{\ 2} + b \cdot \lambda_m + c} \qquad (13)$$

where a, b and c are the quadratic interpolation coefficients of a function through three channels. The greatest disadvantage of the QIBR is the high sensitivity to the noise of the radiance signal.

### d) *Narrow/wide method (N/W)*

Frouin (1989) tested a new Narrow/Wide method for measuring the total water vapor amounts. The ratio was taken between a narrow and a wide band, centered at the same wavelength at the minimum of the absorption band. This method can be modified for the means of imaging spectrometry by ratioing a set of measurement channels $m_i$ to the sum of a larger set ($m_i + r_j$), containing adjacent reference channels (Frouin, 1989):

$$R_{N/W} = \frac{\sum_i L_{m_i}}{\sum_i L_{m_i} + \sum_j L_{r_j}} \qquad (14)$$

Because both, references and measurements are taken within the same absorption band, the signal of the quotient is small, while spectrally varying background reflectance has a little influence on the result.

### e) *Total band ratio (TOTAL)*

The whole set of the selected channels can be used by calculating the ratio between the sum of a number of evaluated measurement channels $m_i$ and reference channels $r_i$ independent of their position in the spectrum (Schläpfer, 1994).

$$R_{TOTAL} = \frac{\sum_i L_{m_i}}{\sum_j L_{r_j}} \qquad (15)$$

### f) *Linear regression ratio (LIRR, see fig. 4)*

The sensor's noise is one of the biggest obstacle to a precise trace gas measurement. The consideration of a maximum number of selected channels reduces this

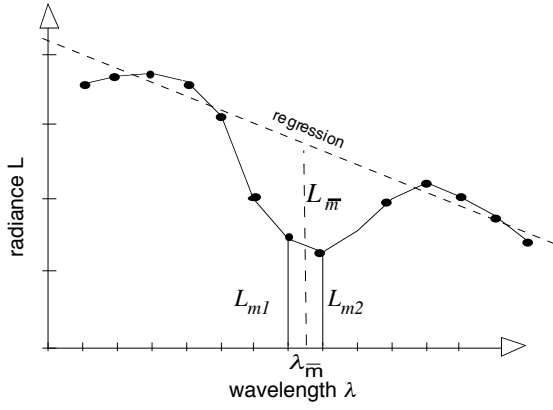fig. 3: *Continuum Interpolated Band Ratio (CIBR)*

fig. 4:    Linear regression ratio (LIRR)

error significantly. A linear regression through a set of reference channels can be taken as interpolation line at the center wavelength of the measurement channels. The LIRR an extension of the CIBR-method by more suitable channels.

$$R_{LIRR} = \frac{L_{\overline{m}}}{b \cdot \lambda_{\overline{m}} + c} \qquad (16)$$

where $L_{\overline{m}}$ is the mean of the signal in the measurement channels with the corresponding mean wavelength $\lambda_{\overline{m}}$ and $b$ and $c$ are the regression coefficients.

## 3.2  Sensitivity analysis

A 'method' is defined as a differential absorption technique based on one specific channel combination set. A good method for the measurement of a trace gas must meet the following requirements:

a) little propagation of sensor noise

b) insensitivity to changing ground reflectance characteristics

c) low cross sensitivity to variations of disturbing atmospheric constituents

d) high sensitivity to varying trace gas amounts

The methods given above are now applied for various channel combinations and tested regarding these requirements. MODTRAN2 simulations of the radiance at the sensor and the AVIRIS sensor characteristics are used as input data. The four evaluation criteria a) to d) are applied to the methods by fixing a limit for each criterion. If a method exceeds one of the limits, it must be excluded from evaluation.

Each of the four criteria is described by a quantitative value. Similar to the channel selection procedure, the methods can be ranked by multiplying these values. If a previously excluded method suddenly appears in the top ranks, it must be included again in the evaluation process.

a) *Noise propagation*

The noise propagation was calculated by applying the Gauss error propagation law to the differential absorption equations. The absolute input error of one channel is the 'gaussian' sum of its noise equivalent radiance and a radiance incertainty due to the background reflectance (see in equation 5). The central wavelengths are assumed to be precise.

The primary sensor noise can be reduced by smoothing the raw data. This can be done by a spatial averaging filter or spectral smoothing by regressive or averaging methods (e.g. LIRR , TOTAL or N/W).

b) *Varying ground reflectance characteristics*

All methods were applied to MODTRAN2 simulated radiance data over water, vegetation and sand, following the 6S reference spectra (Vermote, 1994). The comparison of the results shows the effect of changing underground. The root mean square error of the three resulting values is taken as the evaluation measure.

c) *Atmospheric cross sensitivity*

Other gases and aerosols influence radiance and the methods too. The most absorbing gases (e.g. water vapor for ozone) and the aerosols are varied systematically in the atmospheric profile of the radiance simulation, yielding the errors of the ratio number due to atmospheric variabilities.

d) *Sensitivity to the trace gas amount*

Radiance spectra as a function of the trace gas contents can be simulated by varying the total columnar trace gas contents in the atmosphere, keeping the shape of the profile in the MODTRAN2 simulation constant. The application of the methods to the corresponding simulated spectra yields the sensitivity to the gas of interest of each method. The absolute sensitivity is defined as the difference between ratio values $R(u_1)$ and $R(u_2)$, where $u_1$ and $u_2$ are minimal and maximal possible trace gas concentrations. To obtain a relative sensitivity of a method, this difference is divided by $R(u_2)$. These values can be used to normalize a), b) and c) and as fourth criterion for the method evaluation.

## 3.3  Quantification procedure

The last criterion, which must be considered in the evaluation procedure is the ability to quantify the trace gas contents absolutely using the described MODTRAN2 radiance simulation. It is assumed, that

it must be possible to quantify image ratio values directly in comparison to ratio values corresponding to a known trace gas amount. The dependency of the ratio values from the trace gas amount is approximated by a function given by Frouin (1990), based on the law from Goody and Malkmus:

$$R(u) = a \cdot e^{-k_R \cdot \sqrt{u}} \qquad (17)$$

where $R$ is the Ratio number, $u$ is the columnar trace gas amount [g/m$^2$] and $a$ and $k_R$ are quantification constants.

If the actual image ratio value distribution is out of range compared to the simulated values, the method is not evaluated. The correspondence of image values and simulated values depends strongly on the assumed background reflectance characteristics in the model. So it can occur that chosen ratio methods must be omitted although they showed very good results in the primary exclusive evaluation process.

# 4 RESULTS OF CHANNEL SELECTION

## 4.1 *Channel Selection for Imaging Spectrometry of Ozone*

The broad Chappuis band of ozone between 500 and 700 nm is the only ozone band located within the spectral range of the AVIRIS Sensor (channels 10 to 36). Ozone is intended to be measured only over water because of the small spatial variation of the ground reflectance. The input data is simulated using MODTRAN2 with a standard reflectance spectrum for oligotrophic lakes. Table 1 gives the results of the evaluation using the system of equations described in section 2.

The low sensitivity of the measurement channels is due to the high transmittance of the Chappuis band. The significance can partly be improved by increasing the effective signal to noise ratio. This means that it will be theoretically possible to measure total ozone contents in the Chappuis band only at slightly varying background reflectance (as over lakes) and at enhanced signal to noise ratio in the image (by

| measure ch. no. | wavel. $\lambda$ [nm]. | $M_{sens}$ | $M_{sign}$ | $M_{cross}$ | $M_{meas}$ |
|---|---|---|---|---|---|
| 19 | 578 | 0.038 | 0.171 | 0.995 | 0.0065 |
| 22 | 608 | 0.039 | 0.130 | 0.999 | 0.0051 |
| 21 | 598 | 0.039 | 0.123 | 0.979 | 0.0047 |
| 18 | 568 | 0.037 | 0.094 | 0.996 | 0.0034 |
| ref-chn. | wavel. | $M_{trans}$ | | $M_{noise}$ | $M_{ref}$ |
| 28 | 667 | 0.993 | | 0.948 | 0.941 |
| 15 | 539 | 0.990 | | 0.951 | 0.941 |
| 17 | 558 | 0.988 | | 0.951 | 0.939 |
| 23 | 618 | 0.986 | | 0.951 | 0.938 |

table 1: *The four best preforming measurement channels (top) and reference channels (bottom) for ozone measuring in the Chappuis band (see section 2).*

applying an averaging filter).

## 4.2 *Channel selection for imaging spectrometry of water vapor*

Water vapor has strong absorptance bands especially in the near infrared spectral AVIRIS-range. It was already shown by Kaufmann (1990), that imaging spectrometry of water vapor yields reasonable results over land. Nevertheless, the channel selection is perfomed in the range from 700 to 1350 nm using standard reflectances for vegetation and for oligotrophic lake water. The results are shown in Table 2. The selected channels over water shall serve to determine water vapor contents over lakes complementary to the methods applied over land.

| water vapor measurement: | over vegetation | | over water | |
|---|---|---|---|---|
| measurement channels | 60<br>61<br>82<br>81 | (939 nm)<br>(949 nm)<br>(1151 nm)<br>(1142 nm) | 38<br>60<br>61 | (727 nm)<br>(939 nm)<br>(949 nm) |
| reference channels (near the selected measurement channels) | 52 to 54<br>(529 nm - 549 nm)<br>66 to 73<br>(657 nm - 1074 nm)<br>91 (1238 nm) | | 33 (679nm)<br>40 (746nm)<br>53 (539 nm)<br>66 to 73<br>(657 nm - 1074 nm) | |

table 2: *The best performing measurement and reference channels for water vapor measurement.*

# 5 RESULTS OF METHOD EVALUATION

## 5.1 *Method Evaluation for Imaging Spectrometry of Ozone*

Table 3 shows an extract of the results of the method evaluation for imaging spectrometry of ozone in the Chappuis band. In this list DISLOP and QIBR-Methods do not appear anymore, because their measures were beyond all limits. Especially the quadratic interpolation function is very susceptible to error propagation. Finally two LIRR methods could be evaluated regularly out of the about 40 inspected differential absorption methods. Three other methods were included in the quantification process because of their good total ranking results.

Big discrepancies appeared in trying to quantify the calculated images. None of the considered methods yielded image ratio values comparable to simulated ratio values neither over water nor over vegetation. The image ratio values lie between the simulations for the two ground spectra. Therefore we suppose, that the background reflectance spectrum used for RTC-calibration is the main error source. A

| name of the method plus channel combination | noise propa-gation | varying ground reflect. | atmosph. cross sensitivity | absolute sensitivity | a*b*c / d multiple measure | rank | evaluation result |
|---|---|---|---|---|---|---|---|
| exclusion range: | a > 0.15 | b > 0.15 | c > 2 | d < 0.2 | | | |
| SBR15-19 | x | x | . | . | 1631 | 16 | -n- |
| CIBR 15.28-19 | . | x | x | . | 881 | 6 | -n- |
| CIBR 15.28-22 | . | x | . | . | 392 | 1 | add, -n- |
| CIBR 15.23-19 | x | . | x | . | 2067 | 18 | -n- |
| N/W15.17.23-19.22 | x | x | . | . | 2568 | 22 | -n- |
| TOTAL 15.28-19.22 | . | x | x | . | 950 | 9 | -n- |
| TOTAL 15.17.28-19.21.22 | . | x | . | . | 607 | 4 | add, -n- |
| LIRR 15.16.17.23.28-19.21.22 | . | x | . | . | 396 | 2 | add, -n- |
| LIRR 14:18.23:28-19.22 | . | . | x | . | 897 | 7 | -n- |
| LIRR 14:18.23:28-19.21.22 | . | . | . | . | 553 | 3 | ev |
| LIRR 14:28-19.21.22 | . | . | . | . | 618 | 5 | ev |

*table 3: Results of the exclusion process for the evaluation of ozone measurement methods. All methods with at least one exclusion-'x' are not evaluated. Additional Methods are considered, whenever there ranking was better than the regulary evaluated methods. Terminology: e.g. "CIBR 15.28-22": CIBR-technique with reference channels 15 and 28 and the measurement channel 22. The multiple factor is calculated by multiplying the factors of the evaluation criteria. The codes for the evaluation results are '-n-': not evaluated by exclusion criteria, 'ev': evaluated by exclusion criteria, 'add': evaluated additional by ranking results.*

mixture between water and vegetation ground reflectance would probably give better results.

## 5.2 *Method evaluation for imaging spectrometry of water vapor*

A collection of results of the method evaluation for water vapor measurements is shown in table 4. The best methods from more than 30 investigated ratios are listed together with the evaluation results over lake and over land.

Over water, only one LIRR method can be evaluated. It calculates a linear regression ratio in the weak water vapor absorption band at 730 nm. The noise propagation error is about 7%, whereas all the methods in the 940 nm band show errors of 30% or more due to the lack of ground reflected radiance (here of lake water) at that wavelength. Three additional methods at 730 nm are taken in the quantification process too, but none of them can be

quantified over lake water correctly. That is probably due to the same problem as described for the ozone quantification.

Much better results are achieved over vegetation: Eight methods can be evaluated and two of them can be quantified with good accuracy (see section 6). Their relative noise propagation error over water was 6.7% (CIBR) and 2.6% (LIRR) respectively.

## 6 APPLICATION TO AVIRIS IMAGES

The selected differential absorption methods are finally applied to the AVIRIS'91 scene of Central Switzerland (Meyer, 1994). The used data is very noisy compared with the most recent AVIRIS data. However, it is of a substantial value for atmospherical imaging spectrometry because of the parallel in-situ measurements of atmospheric trace gases, taken in parallel during the POLLUMET experiment (Neininger, 1991). Various balloon soundings in and near the test region were combined to obtain the actual trace

| Name of the method plus channel combination | noise propa-gation | | varying ground reflect. | | atm. cross sens. | | absolute sensitivity | | final results over water | | final results over vegetation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | lake a | veg a | lake b | veg b | lake c | veg c | lake d | veg d | lake meas a*b*c / d | evaluation over lake | veg meas a*b*c / d | evaluation over veg |
| BQ 53-60 | x | . | . | . | . | . | . | . | 1.1 | add, -n- | 0.0 | ev |
| CIBR 36.40-38 | x | x | . | x | . | . | . | x | 3.7 | add, -n- | 0.5 | -n- |
| CIBR 53.67-60 | x | . | x | . | x | . | . | . | 23.3 | -n- | 0.1 | ev |
| CIBR 54.66-60 | x | . | x | . | x | . | . | . | 26.6 | -n- | 0.1 | ev, qu |
| CIBR 54.67-60 | x | . | x | . | x | . | . | . | 27.6 | -n- | 0.1 | ev |
| TOTAL 36.40-37.38 | x | x | x | x | . | . | . | x | 24.0 | -n- | 1.5 | -n- |
| TOTAL 54.66-60.61 | . | . | x | . | . | . | . | . | 7.9 | -n- | 0.0 | ev |
| TOTAL 53.54.66.67-59.60.61.62 | . | . | x | . | x | . | . | x | 14.5 | -n- | 0.1 | -n- |
| LIRR 33:36.40.43-37.38 | . | x | . | x | x | x | . | x | 4.1 | add, -n- | 3.7 | -n- |
| LIRR 33:43-37.38 | . | x | . | x | . | x | . | x | 12.0 | ev | 5.4 | -n- |
| LIRR 53.54.66.67-60.61 | . | . | x | . | x | . | . | . | 18.9 | -n- | 0.1 | ev |
| LIRR 52:54.66:68-60 | x | . | x | . | x | . | . | . | 23.2 | -n- | 0.1 | ev |
| LIRR 52:54.66:68-60.61 | . | . | x | . | x | . | . | . | 17.5 | -n- | 0.1 | ev, qu |
| LIRR 52:54.66:68-59:61 | . | . | x | . | x | . | . | x | 17.9 | -n- | 0.1 | -n- |

*table 4: Results of the exclusion process for the evaluation of water vapor measurement methods. All methods with at least one exclusion-'x' are not evaluated. The codes for the evaluation results are '-n-': not evaluated by exclusion criteria, 'ev': evaluated by exclusion criteria, 'add': evaluated additional by ranking results, 'qu': absolute quantification was performed.*

gas profile for the date of overflight (5th of July, 1991). The error this measurements is supposed to be less than 5%. Additionally, the spatial distribution of ozone and water vapor was measured by in situ flights of an ultra light aircraft.

A critical investigation of the best ozone ratio image calculated by a LIRR 15.16.17.23.28-19.21.22 (see fig. 5) leads to the following remarks:

- Although an absolute quantification was not possible, the image contains good information about the spatial distribution of ozone - the image results are well correlated to in-situ measurements made by a horizontal flying aircraft.

- The image noise was reduced by a factor 9 using an averaging filter of this size. Further, a special filter was applied to the image to eliminate erroneous striping effects, that appeared after the raw calculation. Nevertheless, the high noise is still visible in the patchy structure of the image, and in the southern part of the lake is still a certain striping effect left.

- Some thin cirrus clouds were present and are still visible at the top of the image after processing.

- In the lower right corner there seems to be an area of reduced ozone content. However this effect may be also due to adjacency effects of the mountain slope.

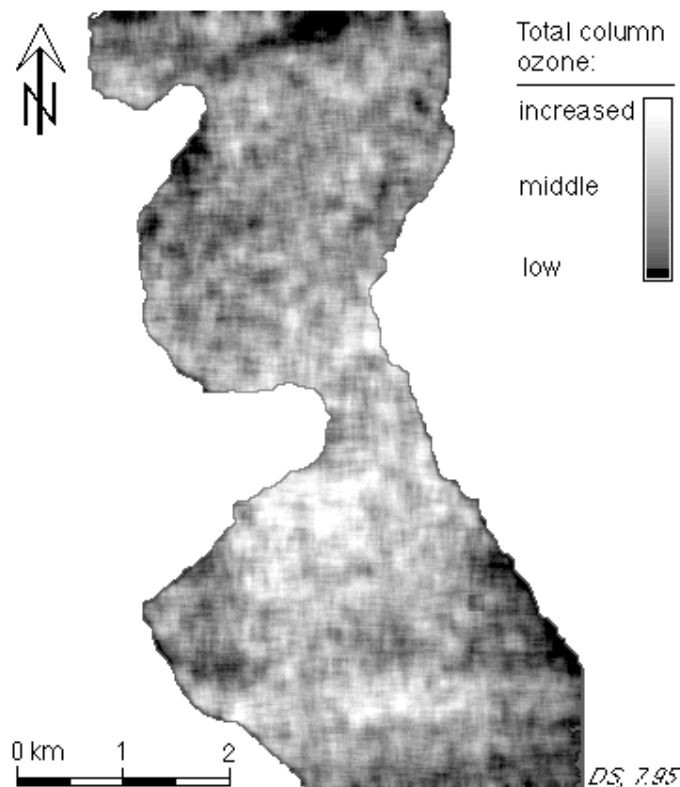These effects induce, that the results have to be taken with caution.
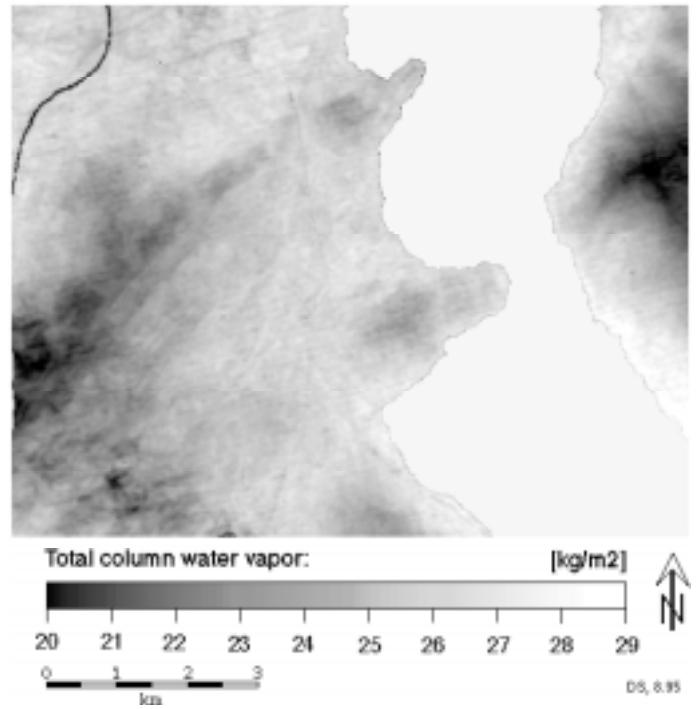


fig. 6:    Absolute quantified column water vapor in the region of Zug, calculated by a linear regression method (LIRR 52:54.66:68-60.61). The water area is masked out.

The quantification results of the LIRR 52:54.66:68-60.61 - method are shown in figure 6. The highest concentrations measured near the lake in the image are about 29 kg/m$^2$ and the mean column near the shore is 28.5 kg/m$^2$. The integration of the measured water vapor profiles taken from radiosonde data yielded a total column of 29.7 kg/m$^2$ over the lake level (414 m a.s.l.). This is a surprisingly good coincidence. It is not clear, whether the difference is a real underestimation of the water vapor content or if it can be attributed to an erroneous calibration due to a to highly concentrated profile.

On the basis of the above numbers, the under-estimation is about 5%. It is a systematic effect which is higher than the noise induced error of about 0.8% at an averaging filtersize of 3x3 pixels. However, it is in the range of the background reflectance error of 6% from 'vegetation' to 'sand'.

The spatial water vapor distribution correlates very well with the DTM of the region. The highest concentrations of water vapor are found in the boundary layer (lower troposphere) with an exponential decrease with height. The difference in height of about 500 m produces a decrease of water vapor. The partial column of about 9 kg/m$^2$ is obtained by integrating the calibration profile between 414 and 954 m a.s.l. as well as by the image results.



fig. 5:    Relative total ozone contents over lake Zug, calculated by a linear regression method (LIRR   15.16.17.23.28-19.21.22).

# 7 CONCLUSIONS AND OUTLOOK

A new quantitative method of channel selection yielded ranged sets of channels for imaging spectrometry of ozone and water vapor. The combinations of the evaluated measurement and reference channels in various ratio methods was evaluated using an exclusion and a ranking process. Applying the radiative transfer code MODTRAN2, the selected methods were calibrated to the total trace gas columns at standard ground reflectance spectra. The evaluation was applied to the specific characteristics of the AVIRIS sensor, but the methodology can be applied to other sensors too. Furhermore, it is not restricted to ozone and water vapor measurement but contains common tools of channel selection and method evaluation for any atmospheric trace gas (e.g. carbon dioxide or methane). The methodology has the potential of being used in terrestrial applications (e.g. chlorophyll measurements, limnological applications, etc.) too.

The quantification of water vapor over land is possible with an accuracy of ±6%. The underestimation is attributed to the uncertainty in background reflectance or aerosol concentration. The distribution with terrain height is very similar to the profile measured by balloon sondes, although the image was calibrated by the ingegrated total water vapor column (the slope of the trace gas profile has a negligible effect on the results). Hence, the used methodology has the potential to derive water vapor profiles from the boundary layer, using the digital terrain model. In a next step a three dimensional modelling of the water vapor field in a valley will be possible. The complementary measurement of water vapor over lakes will only be possible with further improvements of the methodology.

The measurement of ozone by the selected method could not be quantified absolutely neither over water nor over land. Over land the influences of the background reflectance was much higher than the signal of the ozone absorption. Even over water with nearly constant reflectance distribution, the adjacent and inherent vegetation (resp. Chlorophyll) signal seems to have its impact on the resulting image. Nevertheless the measured relative ozone distribution over lake agree with the in-situ measurements. The measurement of ozone can be improved by applying an adjacency correction to the images or using images of better SNR's. A new approach would be the use of an imaging spectrometer which has channels in the stronger absorbing Huggins band located in the UV-range of the spectrum.

Another scope will be to develop new measurement methods, which differ essentially from the differential absorption techniques. The application of linear spectral unmixing processes would be the most promising approach. The basic method is now described and will be applied to more recent AVIRIS data, tested with other sensors and extended to other trace gases or aerosols.

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