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IMAGING SPECTROMETRY OF TROPOSPHERIC OZONE: METHODOLOGY OF CHANNEL SELECTION

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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 particularly in the ultraviolet and visible range of the spectrum. Hence, spectrometry is expected to be a promising tool to extract the ozone 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. A new mathematical method of channel selection for measuring atmospheric trace gases by imaging spectrometry is presented and applied to data corresponding to ozone measurements.

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). 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). The AVIRIS is sensitive in 224 channels located between 400 and 2455 nm with a resolution of 10 nm. Based on this data, investigations to detect tropospheric ozone in the Chappuis-Band (500 - 700 nm) were initiated.

Since experiments with 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 is calculated by MODTRAN2 simulations (Berk, 1989). The imaging spectrometer channels are then evaluated by searching the best suitable wavelength regions of the spectrum.

The optical measurement of atmospheric trace gases is usually performed with 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). They perform a ratioing between influenced channels within the absorption band (*measurement channels*) to non influenced channels beside of 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 are not influenced by any absorbing gases. The various ratioing methods differ from one another by the number of selected channels and by the calculation procedure.

The objective of this work is to select in a optimal manner the measurement and the reference channels by quantifying their requirements. The conditions are written in mathematical form and the channels are selected by optimizing the corresponding equations.

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*

a) *Sensitivity*: The change of the transmittance T_m due to a variation of the total column u_m of the trace gas m follows directly from the Beer-Lambert law:

$$T_m = e^{-k_m \cdot u_m} \rightarrow \frac{\partial T_m}{\partial u_m} = -k_m T_m = \frac{\ln T_m}{u_m} \cdot T_m \quad (1)$$

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

$$M_{sens} = -e \cdot \ln T_m \cdot T_m \quad (2)$$

b) *Significance*: The significance factor M_{sign} is defined as

$$M_{sign} = \frac{(L_{A,m} - L_S) - \Delta L_S}{L_{A,m} - L_S} \quad (3)$$

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. ΔL_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 ρ . For the significance factor follows

$$M_{sign} = 1 - \frac{1}{L_{A,m} - L_S} \sqrt{(L_{NER})^2 + \left(\frac{\Delta\rho}{\rho} \cdot L_{S,dir}\right)^2} \quad (4)$$

where $L_{S,dir}$ 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 :

$$M_{cross} = \prod_a (T_a) \quad (5)$$

The three effects described in the equations (2), (4) and (5) are now combined to get the channel qualifier M_{meas} for the measurement channels:

$$M_{meas} = M_{sens} \cdot M_{sign} \cdot M_{cross} \quad (6)$$

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:

$$M_{trans} = T_m \cdot \prod_a (T_a) \quad (7)$$

b) *Noise*: Similar to the significance factor M_{sign} the noise factor M_{noise} is based on the effective noise at the sensor:

$$M_{noise} = 1 - \frac{1}{L_s} \sqrt{(L_{NER})^2 + \left(\frac{\Delta\rho}{\rho} \cdot L_{S,dir}\right)^2} \quad (8)$$

Analogous to (6) the measures (7) and (8) are multiplied to evaluate the reference channels:

$$M_{ref} = M_{trans} \cdot M_{noise} \quad (9)$$

Channel Selection for Imaging Spectrometry of Ozone

In the broad Chappuis band of ozone between 500 and 700 nm there are more than 20 AVIRIS channels available. 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 described system of equations.

mea-chn.	wavel. [nm].	M_{sens}	M_{sign}	M_{cross}	M_{meas}	ref-chn.	wavel. [nm].	M_{trans}	M_{noise}	M_{ref}
19	578	0.038	0.171	0.995	0.0065	28	667	0.993	0.948	0.941
22	608	0.039	0.130	0.999	0.0051	15	539	0.990	0.951	0.941
21	598	0.039	0.123	0.979	0.0047	17	558	0.988	0.951	0.939
18	568	0.037	0.094	0.996	0.0034	23	618	0.986	0.951	0.938

Tab 1: The four best performing measurement channels (left) and reference channels (right) for ozone measuring in the Chappuis Band.

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 applying an averaging filter).

Conclusions

The new quantitative method of channel selection yielded a ranged set of channels for imaging spectrometry of ozone. They can be combined subsequently in various ratio methods. These ratios can be calibrated to ozone columns using atmospheric radiation transfer codes such as MODTRAN2. The applied methodology is not restricted to ozone measurement. It is a common tool of channel selection for any atmospheric trace gas (e.g. water vapor, carbon dioxide or methane). Furthermore, the methodology has the potential of being used for channel selection in terrestrial applications (e.g. chlorophyll measurements, limnological applications, etc.).

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