# THE ATMOSPHERIC SENSITIVITY OF THE AIRBORNE IMAGING SPECTROMETER APEX

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## ABSTRACT

The new airborne imaging spectrometer APEX will be available in 2006. It observes the visible and shortwave infrared spectral ranges. With its unique combination of spectral and spatial resolution, atmospheric molecular spectroscopy is feasible with unprecedented spatial resolution and coverage. Sensitivity calculations show, that atmospheric columns of $NO_2$ and $CH_4$ will be quantified with a spatial resolution of about 30 m. Such observations open new possibilities in the characterization of sub-satellite pixel distributions and air pollution monitoring. $H_2O$ and $CO_2$ may also be observed. Additionally, a large set of atmospheric aerosol and cloud properties can be measured.

## 1. INTRODUCTION

The Airborne Prism EXperiment (APEX) is an airborne dispersive push broom imaging spectrometer for the hyperspectral observation of ground reflectances [e.g., Nieke et al., 2004]. APEX is currently being built in a joint Swiss/Belgian project funded through the ESA PRODEX program. It will be operated by VITO, Belgium, starting from 2006.

The spectrometer records up to 511 spectral points in the wavelength range 380–2500 nm with a sampling interval of 0.4 to 10 nm. A CCD and a CMOS are used as detectors in the visible/near infrared (VNIR) and shortwave infrared (SWIR) spectral ranges, respectively. The ground pixel size ranges from 2 to 5 m corresponding to flight altitudes of 4 to 10 km. Since APEX is a push broom instrument all spectral points for all 1000 across-track pixels are observed simultaneously. A dedicated calibration laboratory is being built to facilitate the absolute calibration of the instrument. For more details visit the instrument homepage http://www.apex-esa.org.

APEX achieves an unprecedented combination of good spatial and spectral resolutions, coverage, and signal to noise ratio. Thus a large number of atmospheric parameters may also be retrieved from its measurements. In this paper, we give an overview of potential atmospheric applications of APEX and calculate theoretical precisions for the retrieval of columns of the trace gases $NO_2$, $O_3$, and $CH_4$.

## 2. OVERVIEW OF ATMOSPHERIC APPLICATIONS

Even though APEX primarily aims at the observation of the surface reflectance, atmospheric applications have already been taken into account during the definition of the instrument requirements [Schläpfer and Schaepman, 2002]. Figures 1 and 2 give an overview of the optical depths of the total zenith atmosphere of various atmospheric constituents in the spectral range of APEX. The values are calculated with MODTRAN [e.g., Berk et al, 1998], modeling mid-latitudinal atmospheric profiles for summer and 360 p.p.m. $CO_2$. They are convolved to the spectral resolution of APEX. The center band wavelengths are indicated by vertical red lines.

### 2.1 Trace gases

Owing to APEX' good spectral resolution the spectral signatures of several trace gases can be observed. The optical depths of water vapor, oxygen, and carbon dioxide obviously display strong signatures that can be analyzed in the observed spectra. They can be used for the atmospheric correction of the observation, i.e. the retrieval of the surface reflectance.

Nitrogen dioxide, ozone, and methane have optical depths that are hardly discernible in the total optical depth. They are, however, of particular importance for the monitoring of local and regional air pollution [e.g., Schaub et al., 2005, Heldstab et al., 2004]. Section 3 of this work quantitatively analyses their expected retrieval precisions.

### 2.2 Aerosols

The optical depth of typical aerosols displays a spectrally smooth signature. This characteristic is sometimes used to distinguish aerosol parameters from the underlying land surface reflectance [e.g., von Hoyningen-Huene et al., 2003, for SeasWiFS]. However, the optical depth varies considerably over the relatively large spectral range observed by APEX, which is indirectly used by the MODIS aerosol retrieval over land [Kaufman et al., 1997]. Additionally, the observations at small wavelengths, starting with 380nm show a relatively (as compared to the surface reflectance) strong aerosol influence, which is used, e.g., by Höller et al. [2004] for analyzing observations by the Global Imager (GLI) aboard JAXA's ADEOS-II satellite. Since all these different algorithms can be applied to APEX observations, the aerosol product can be improved by combining information extracted with several algorithms.

### 2.3 Clouds

APEX will observe variations in the radiance field due to the scattering by structured clouds at spatial scales

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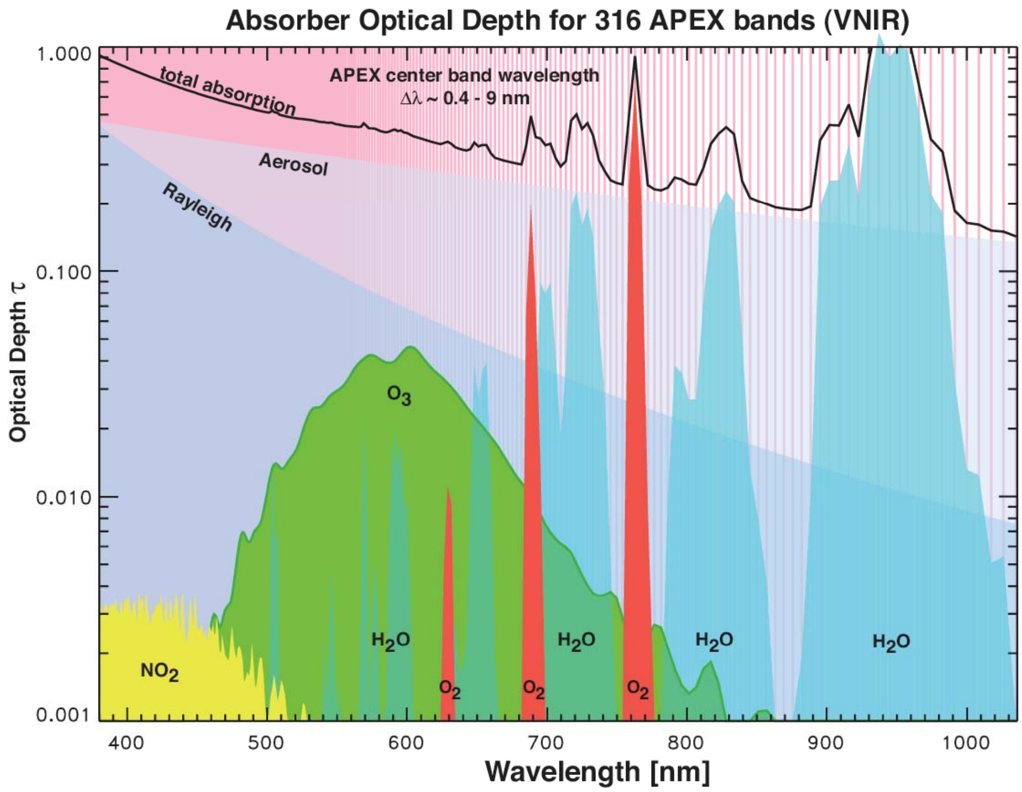


**Fig. 1. Atmospheric Constituents' Optical Depths Seen by APEX' VNIR Channel.**

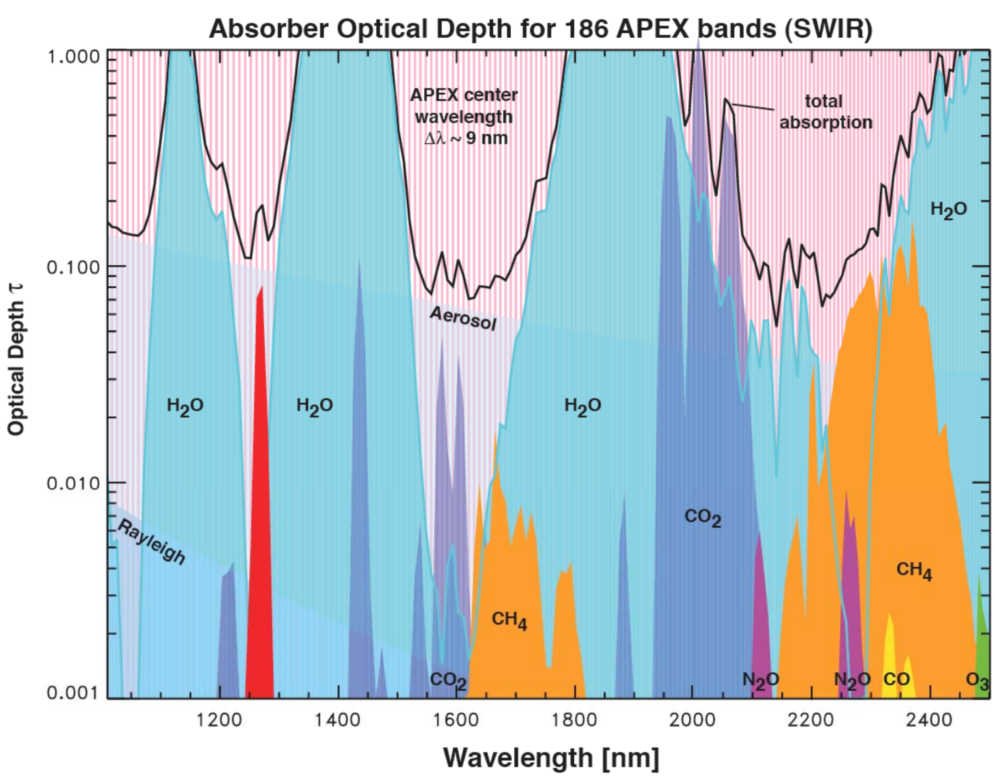


**Fig. 2. Atmospheric Constituents' Optical Depths Seen by APEX' SWIR Channel.**



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to the scattering by structured clouds at spatial scales ranging from about 1 m to several km simultaneously, e.g., von Savigny et al. [2002] have analyzed the radiative smoothing using a time series of zenith sky radiances under clouds. With APEX such analyses can be extended by observing a 2-dimensional field of up-welling radiances over a large spectral range.

## 3. THEORETICAL PRECISIONS FOR TRACE GAS OBSERVATIONS

### 3.1 Method

Theoretical retrieval precisions are calculated for the column densities of $NO_2$, $O_3$, and $CH_4$ assuming a least squares retrieval algorithm. The analysis is performed separately for each molecule, considering the fit windows listed in Table 2. The flow of the analysis is pictured in Figure 3 and described below. The assumed parameters are detailed in Table 1.

First, the observed spectrum $\mathbf{y_t}$ and its Jacobian $\mathbf{K_t}$, i.e. the matrix of derivatives w.r.t. the trace gas concentrations in the assumed trace gas profile $\mathbf{x}$, are simulated with a radiative transfer model. Fitting a polynomial to the spectrum $\mathbf{y}_t$ and subtracting it from the spectrum separates the differential molecular absorption signature $\mathbf{y}$ from the other, broadband effects in a DOAS-type fashion. The Jacobian $\mathbf{K}$ of $\mathbf{y}$ is calculated analogously by fitting and subtracting polynomials.

Typical signal to noise ratios of APEX are taken from the critical design review documents of APEX. They are combined with the simulated spectrum $\mathbf{y_t}$ to obtain the measurement covariance matrix $\mathbf{S_y}$, which is assumed to be diagonal. The least squares formalism provides the inverse of the retrieval error covariance matrix $\mathbf{S_x}$:

$$\mathbf{S_x}^{-1} = \mathbf{K}^T \mathbf{S_y}^{-1} \mathbf{K} .$$

The matrix $\mathbf{S_x}^{-1}$ cannot be inverted directly as the observation does not provide enough information to resolve the layers of the atmospheric profile. Thus real retrievals will have to be regularized with additional information, e.g., by scaling an a priori profile in a DOAS-type algorithm [Platt, 1994] or with an optimal estimation scheme [Rodgers, 2000]. Then any retrieved profile can be interpreted as indirect measurement of the total trace gas column. For the purpose of estimating the total column retrieval precision inherent to the APEX measurements the least squares formalism can be applied to $\mathbf{S_x}^{-1}$: The variance $\sigma_{col}^2$ of the total column retrieval error is expressed as

$$\sigma_{col}^2 = (\mathbf{K}_{col}^T \mathbf{S_x}^{-1} \mathbf{K}_{col})^{-1} ,$$

where $\mathbf{K}_{col}$ denotes the Jacobian of the profile-to-column conversion. Note, that it contains only one row as only one parameter is retrieved, i.e. the trace gas column. Finally, $\sigma_{col}$ is interpreted as theoretical retrieval precision. It should be noted that it represents the best case in which the measurement noise dominates the total retrieval error.

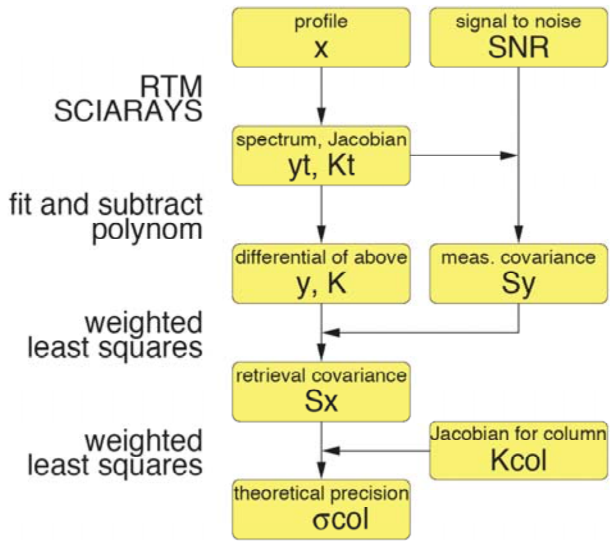


**Fig. 3. Flow of Analysis.**

**Table 1. Measurement and Retrieval Scenario**

| | |
|---|---|
| atmospheric profiles | mid-latitude |
| solar zenith angle | 30 deg |
| surface albedo | 30% |
| flight height | 6km |
| signal/noise ratio | 150–470 |
| subtracted polynomial | 3rd order |

All calculations are performed with an adapted version of the toolbox SCIARAYS, which contains a radiative transfer model, an instrument model, and inversion routines [Kaiser and Burrows, 2003].

### 3.2 Results

The calculated theoretical retrieval precisions in absolute units [$cm^2$] are summarized in Table 2. Column 4 gives the precision for retrievals from individual pixels of the APEX observation. For the assumed flight altitude of 6 km. This corresponds to a ground pixel size of 3 x 3 $m^2$. Additionally, column 5 shows the precisions for an average of 100 pixels. This would correspond to a ground pixel size of, e.g., 30 x 30 $m^2$. It enhances the retrieval precision by a factor of 10.

Column 3 provides a comparison to typical atmospheric values observed by SCIAMACHY with a ground pixel size of 30 x 60 $km^2$ [Bovensmann et al., 2003, and references therein].

The range of typical atmospheric $NO_2$ columns represents both polluted and background situations. Substantially larger values are expected once the sub-SCIAMACHY-pixel structure of the $NO_2$ pollution is resolved. The $NO_2$ retrieval from individual APEX pixels will have a precision of the background's order of magnitude. It is expected that such analyses are only useful in the case of strong local emission sources. However, retrievals with a spatial resolution of 30m will yield $NO_2$ column information



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**Table 2. Theoretical Column Retrieval Precisions**

| | fit window [nm] | atmospheric column [$cm^{-2}$] | theoretical precision [$cm^{-2}$] 3m x 3m | theoretical precision [$cm^{-2}$] 30m x 30m |
|---|---|---|---|---|
| $NO_2$<br>$O_3$<br>$CH_4$ | 420–480 550–620 1640–1740 | $0.5–1.0 \times 10^{16}$<br>$1 \times 10^{19}$<br>$2 \times 10^{19}$ | $6 \times 10^{15}$<br>$2 \times 10^{18}$<br>$1 \times 10^{19}$ | $6 \times 10^{14}$<br>$2 \times 10^{17}$<br>$1 \times 10^{18}$ |

with a precision of about 10% in most observational situations.

Considering that the tropospheric contribution to the total column of $O_3$ is relatively small, the retrieval precision of 20% for 3m spatial resolution is not considered to be useful. The precision of 2% for 30 m spatial resolution might be sufficient to study extreme events of ozone smog.

The retrieval of $CH_4$ with 3m ground resolution shows a precision of 50%, which may facilitate the qualitative detection of strong $CH_4$ sources. Quantitative studies are possible with observations averaged to about 30m spatial resolution. Additional information on $CH_4$ can be expected from the absorption band around 2350 nm wavelength.

All mentioned precision values correspond to the maximal potential accuracy achieved under idealized experimental conditions. The realization of such accuracy when analyzing real measurements will strongly depend and the actual conditions, e.g., underlying surface reflectivity. Anyway it will be a challenging task.

## 4. CONCLUSIONS

The airborne imaging spectrometer APEX will record atmospheric radiance spectra in the wavelength range 380–2500 nm with a spectra resolution varying between 0.5 and 10 nm. The spectra are recorded simultaneously for 1000 across-track pixels with a pixel size of 2–5 m depending on flight altitude. The instrument will become operationally available in 2006.

The observations offer a unique opportunity to quantitatively observe the tropospheric distributions of the atmospheric trace gases $NO_2$ and $CH_4$ with a resolution of a few meters while covering regions of several kilometers extent. This is a new possibility to monitor local and regional air pollution. Additionally, the distributions within entire satellite pixels may be characterized to validate the satellite instrument products and facilitate the down/up-scaling. Trace gas profile information may be obtained by observing the same scene with several flight altitudes.

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## REFERENCES

Berk, A., et al., MODTRAN cloud and multiple scattering upgrades with applications to AVIRIS. *Remote Sensing of Environment*, **65**, 367–375, 1998.

Bovensmann, H., et al., SCIAMACHY on ENVISAT: In-flight optical performance. *Proc. SPIE*, **5235,** 160–173, 2003.

Heldstab, J., et al., *Modelling of NO2 and benzene ambient concentrations in Switzerland 2000 and* 2020. Swiss Agency for the Environment, Forests and Landscape SAEFL, CH-8003 Berne, 2004.

Höller, R., et al., The GLI 380-nm channel application for satellite remote sensing of tropospheric aerosol. In *The 2004 EUMETSAT Meteorological Satellite Conference*, 2004.

Kaiser, J.W. and J.P. Burrows. Fast weighting functions for retrievals from limb scattering measurements. *J. Quant. Spectrosc. Radiat. Transfer*, **77**(3), 273–283, 2003.

Kaufman, Y.J., et al.. The MODIS 2.1 µm channel correlation with visible re- flectance for use in remote sensing of aerosol. *IEEE Trans. Geosci. Remote Sensing*, **35**(5), 1286–1298, 1997.

Nieke, J., et al., APEX: Current status of the airborne dispersive pushbroom imaging spectrometer. *Proc. SPIE*, **5542**, 2004.

Platt, U. Differential Optical Absorption Spectroscopy (DOAS). In: *Air Monitoring by Spectroscopic Techniques, Chem. Anal.*, **127,** 27–76, John Wiley, New York, 1994.

Rodgers, C.D. *Inverse Methods for Atmospheric Sounding: Theory and Practice*. World Scientific, Singapore, 2000.

Schaub, D., et al., A transboundary transport episode of nitrogen dioxide as observed from GOME and its impact in the Alpine region. *Atmos. Chem. Phys.*, **5,** 23–37, 2005.

Schläpfer, D., and M. Schaepman. Modeling the noise equivalent radiance requirements of imaging spectrometers based on scientific applications. *Appl. Opt.*, **41**(27), 5691–5701, 2002.

von Hoyningen-Huene, W., et al., Retrieval of aerosol optical thickness over land surfaces from top-of-atmosphere radiance. *J. Geophys. Res. A*, **108**(D9), 4260, 2003.

von Savigny, C., et al., Time-series of zenith radiance and surface flux under cloudy skies: Radiative smoothing, optical thickness retrievals and large-scale stationarity. *Geophys. Res. Lett.*, **29**(17), 1825–1828, 2002.



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