# COMBINED OZONE RETRIEVAL USING THE MICHELSON INTERFEROMETER FOR PASSIVE ATMOSPHERIC SOUNDING (MIPAS) AND THE TROPOSPHERIC EMISSION SPECTROMETER (TES)


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## ABSTRACT

The main advantage in combining limb and nadir geometries is that it allows the stratospheric and tropospheric ozone concentrations to be separated which makes it possible to improve the tropospheric ozone retrieval. This paper presents the retrieval method which will be used to combine TES nadir measurements with MIPAS limb measurements and shows some preliminary results.

The Tropospheric Emission Spectrometer (TES) is a high-spectral-resolution infrared imaging Fourier transform spectrometer operated by NASA's Jet Propulsion Laboratory(JPL). It has a spectral range from 3.2$\mu$m to 15.4$\mu$m and at present is mostly operating in the nadir mode. TES routinely measures temperature and concentrations of $O_3$,$H_2O$, $CH_4$, CO, $HNO_3$, and $N_2O$.

A local optimal estimation retrieval code (the MIPAS Orbital Retrieval using Sequential Estimation (MORSE)) was used to retrieve Volume Mixing Ratios (VMR's) from the low resolution ESA level 1B MIPAS data and level 1B TES data. A joint retrieval was achieved by using the MIPAS retrieved VMR profiles as the *a priori* for the TES retrieval. A similar method could be used in the future to combine MIPAS and IASI.



Key words: Joint retrieval; TES; MIPAS.


## 1. INTRODUCTION

Limb viewing instruments have a longer path length than nadir viewing instruments, which allows them to detect smaller concentrations of trace gasses which can not be detected by nadir viewing instruments. However the longer the path length through the atmosphere the greater the possibility of the scan being contaminated by clouds for the lower altitudes. Therefore limb geometries provide better stratospheric retrievals whereas nadir geometries produce better tropospheric retrievals.

Combining limb and nadir measurements takes advantage of the strengths of both viewing geometries. This makes it possible to separate out the stratospheric ozone contribution to the total ozone column allowing for a better tropospheric ozone retrieval.

### 1.1. The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) is a high resolution Fourier transform spectrometer which was launched on 1st March 2002 on ESA's ENVISAT satellite. MIPAS measures atmospheric limb emission in the infrared range of 4.1–14.5$\mu$m, which is split into 5 bands. MIPAS routinely performs retrieval of pressure and temperature, as well as the volume mixing ratio (VMR) of six high-priority species ($O_3$, $H_2O$, $HNO_3$, $CH_4$, $N_2O$ and $NO_2$) [2]. MIPAS is capable of viewing both in the rearward (routine scans) and sideways modes (Fig.1). Originally MIPAS operated at a spectral sampling of 0.025 $cm^{-1}$ but due to mechanical problems has been operating at a reduced resolution of 0.0625 $cm^{-1}$ since August 2004.

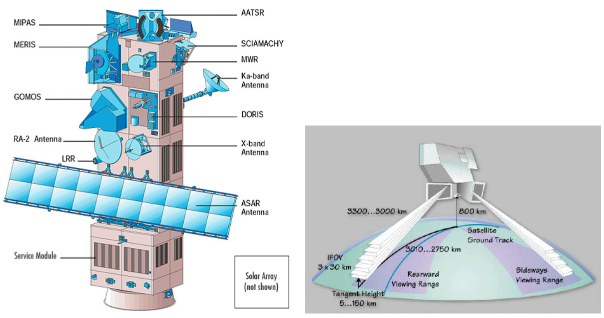


*Figure 1. The figure on the left shows the location of each instrument on the ENVISAT satellite while the figure on the right shows the viewing directions that MIPAS is capable of. [ESA ENVISAT website]*

### 1.2. The Tropospheric Emission Spectrometer (TES)

The Tropospheric Emission Spectrometer (TES) is a high-spectral-resolution infrared imaging Fourier transform spectrometer developed, built, tested and operated by NASA's Jet Propulsion laboratory (JPL) [1]. Launched in July 2004 on NASA's AURA satellite TES has a spectral range from 3.2$\mu$m to 15.4$\mu$m and is able to perform both limb and vertical measurements of the atmosphere (Fig.2). When viewing in the nadir TES covers an area of approximately $5.3$km by $8.3$km and as TES is a pointable instrument it can access any target within $45$ degrees of the local vertical [TES website]. TES routinely measures temperature, concentrations of $O_3$, $H_2O$, $CH_4$, CO, $HNO_3$ and $N_2O$. TES runs a global survey consisting of 16 orbits of nadir scans and calibrations scan on a one-day on one day off schedual, with special observation scans run on the off-days.

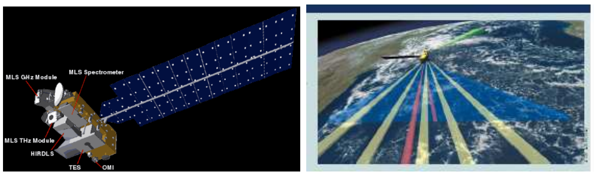


*Figure 2. The figure on the left shows the position of each of the instruments on the Aura Satellite while the viewing geometry's of each instrument are shown in the figure on the right (red=TES, blue=OMI, yellow=HIRDLS and green=MLS). [TES website]*

## 2. RETRIEVALS METHODOLOGY

A local optimal estimation retrievals code (the MIPAS Orbital Retrieval using Sequential Estimation (MORSE)) is used to retrieve Volume Mixing Ratios(VMR) from the low resolution ESA level 1B MIPAS data. All standard MIPAS species will be retrieved as well as $N_2 0_5$, $ClONO_2$ , CFC11 and CFC12 on an altitude grid from 0-68km with step size from 1.5–4.5km. This retrievals uses the Oxford Reference Forward Model (RFM) and the same set of microwindows as the ESA operational retrieval. The optimal estimation method constrained the solution to be close to the *a priori* solution, in this case a standard climatology atmosphere. The solution is found by minimising the cost function $\chi^2$ (Eq.1) through an iterative method where the state vector is amended after each iteration according to Eq.2 [Rodgers 2000].

$$\chi^2 = (\mathbf{y} - \mathbf{F}(\mathbf{x}))^T \mathbf{S}_y^{-1} (\mathbf{y} - \mathbf{F}(\mathbf{x})) + (\mathbf{x} - \mathbf{a})^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{a}) \quad (1)$$

$$\mathbf{x}_{i+1} = \mathbf{x}_i + (\mathbf{S}_a^{-1} + \mathbf{K}^T \mathbf{S}_y^{-1} \mathbf{K})^{-1} [\mathbf{K}^T \mathbf{S}_y^{-1} (\mathbf{y} - \mathbf{F}(\mathbf{x}_i)) - \mathbf{S}_a^{-1} (\mathbf{x}_i - \mathbf{x}_a)] \quad (2)$$

Where $\mathbf{F}(\mathbf{x})$ is the forward model estimate, $x$ is the retrieval state vector, y is the measured spectrum, **a** is the *a priori* estimate and $\mathbf{S}_y$ and $\mathbf{S}_a$ are the covariances of **y** and **a** respectively.

This method is less sensitive to noise than other methods, but can introduce an a priori bias into the profiles. Fig.3 shows the mechanism of the retrieval process.

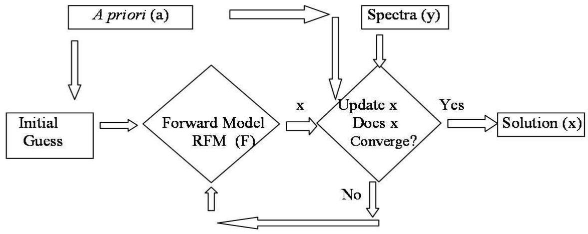


*Figure 3. This flow chart depicts the various stages in an optimal estimation retrieval.*

The TES nadir retrieval uses a similar optimal estimation retrieval code to the MIPAS retrieval to retrieve temperature, ozone and water vapour profiles as well as surface temperature and pressure. The microwindows used were selected on information content relative to the retrieved species. This retrieval also used the Levenberg-Marquardt method to reduce the chance of the retrieval from not converging, by updating the state vector by a smaller step if the $\chi^2$ value increases from one iteration to the next. Therefore state vector for the retrieval is update after each iteration using Eq.3 [Rodgers 2000] .

$$\mathbf{x}_{i+1} = \mathbf{x}_i + [(1+\gamma)\mathbf{S}_a^{-1} + \mathbf{K}^T \mathbf{S}_y^{-1} \mathbf{K}]^{-1} \mathbf{K}^T \mathbf{S}_y^{-1} [\mathbf{y} - \mathbf{F}(\mathbf{x}_i)] - \mathbf{S}_a^{-1} [\mathbf{x}_i - \mathbf{x}_a] \quad (3)$$

The TES nadir retrieval retrieve VMR on an altitude grid from 0- 60 km with a step size of 3km up to 30km and 5km above that. The retrieval uses climotology values are used for all altitudes above 60km.

The joint retrieval was achieved by using the MIPAS retrieved atmospheric profiles as the *a prior* for the TES nadir retrieval. The joint retrievals were achieved by using the MIPAS retrieved temperature, pressure and ozone profiles as the a priori for the TES nadir retrievals. The MIPAS retrieved profiles are on a slightly different altitude grid from that of the TES nadir retrievals so the profiles and the corresponding covariances were interpolated to the TES altitude grid (Eq.4-5). This particular MIPAS scan was flagged as cloudy for altitudes up to 15 km, therefore climotology values where used as the *a priori* for those altitudes.

$$\mathbf{x}' = \mathbf{B}\mathbf{x} \quad (4)$$

$$\mathbf{S}_x' = \mathbf{B}\mathbf{S}_x\mathbf{B}^T \quad (5)$$

Where **x** is the state vector, $\mathbf{S}_x$ is the covariance of the state vector and **B** is the grid transformation matrix

### 2.1. TES microwindow selection

To select the microwindows for the TES nadir retrieval a simulated spectrum, covering the TES spectral range, was split into three wavenumber-wide microwindows. The information content was calculated for surface temperature, pressure, temperature, ozone and water vapour for each microwindow using the Eq.6 [Rodgers 2000].

$$\text{Information content} = -0.5 log \frac{|\mathbf{S}_x|}{|\mathbf{S}_a|} \tag{6}$$

$$\mathbf{S}_x = (\mathbf{K}^T \mathbf{S}_y^{-1} \mathbf{K} + \mathbf{S}_a^{-1})^{-1} \tag{7}$$

Where $\mathbf{S}_x$ and $\mathbf{S}_a$ are the covariances of the state vector, given by Eq.7, and the *a priori* respectively. The four microwindows with the largest total information content were selected for the TES nadir retrieval, and consisted of three in the 2000-2300 wavenumber region and one in the 1000 wavenumber region. Fig.4 shows the spectral location of these four microwindows and the corresponding information content for a joint retrieval of surface temperature, pressure, ozone, water vapour and atmospheric temperature profile. The information content is shown in coloured blocks to indicate which species that information relates too.

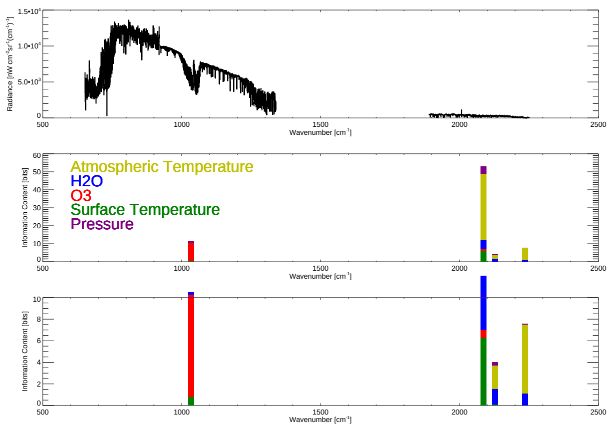


*Figure 4. The top plot shows a typical TES nadir spectrum . The middle plot shows the location of the four selected microwindows and the corresponding information content for a joint retrieval of surface temperature, pressure, ozone, water vapour and atmospheric temperature profiles. The bottom plot is a blown up version of the above plot. The width of the microwindows has been increased by 10 cm$^{-1}$ from the central point for this plot.*

## 3. PROFILE SELECTION

The brightness temperature of the scan was used to determine if that scan was over clear sky (high brightness temperature indicating clear sky and low brightness temperature indicating that there are probably clouds in that view). Fig.5 shows that brightness temperature of each scan made on the 28th January 2005.

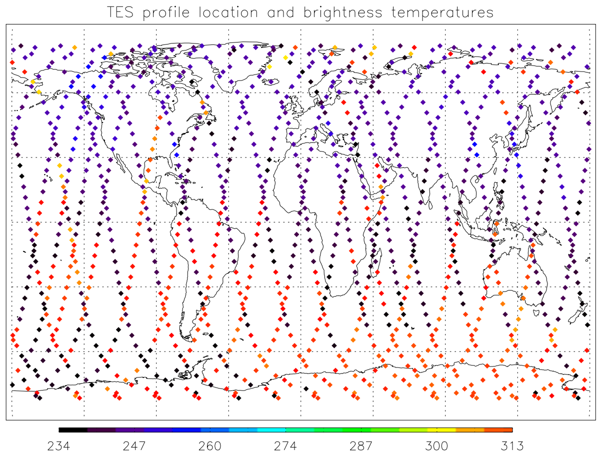


*Figure 5. This plot shows the geolocation of each TES nadir scan for the 28th January 2005. Two nadir scans are performed at each location and the colour scale indicates the brightness temperature of the scan.*

There are several regions where several susessive scan have a hight brightness temperature. One scan (51) from the centre of one such region from orbit 2855 was chosen for the first test retrieval using TES L1B data. Clean sky profiles have been selected for this study to avoid cloud contamination of the measurements at the lower altitudes. This profile was also selected to be over the ocean to avoid any complications due to retrieving over land. The closest MIPAS scan to this selected TES scans has been selected for this study.

## 4. INITIAL RETRIEVAL RESULTS

A TES nadir retrievals was run using the retrieval scheme previously described and the selected microwindows using the TES l1B data for scan 51 of orbit 2855 for the 28th January 2005. The retrieved ozone and temperature profiles are shown in the Fig.6 along with the climatology profiles and the retrieved profiles from the closest scan to the TES profile.

The TES Stratospheric ozone is slightly higher than both the MIPAS retrieval and the climatology profile, which agree well with each other in the stratospheric region. It can be seen that there is a problem with the TES nadir retrieval at low altitudes, TES is retrieving a large peak in ozone of approximatly 2ppm in the 7km region. This may be due to some kind of cloud contamination or a lack of information on the tropospheric region in the microwindows used for this retrieval.

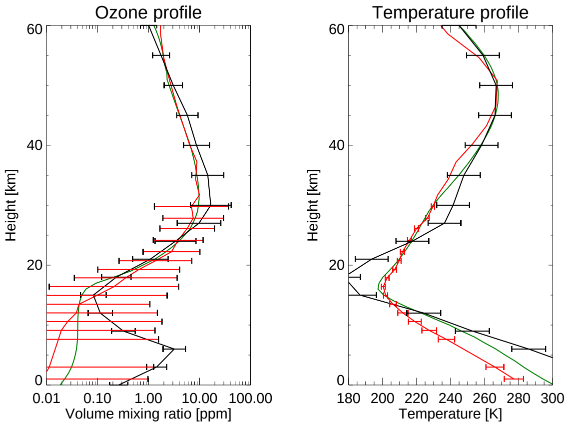


*Figure 6. This plot shows the TES nadir retrievals(black), the MIPAS limb retrieval(red) and a climatological profile(green) for ozone (left-hand panel) and temperature (right-hand panel) for the 28th January 2005.*

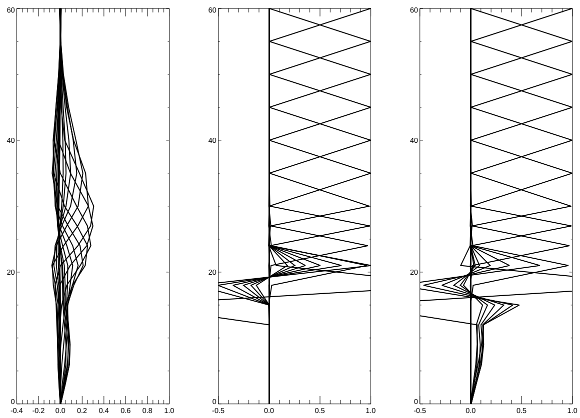

*Figure 7. This plot shows the averaging kernels calculated for the measurement and a priori covariances of the TES nadir retrieval (left-hand panel), the MIPAS limb retrieval (middle panel) and for a combined retrieval (right-hand panel)*

## 5. AVERAGING KERNELS

The averaging kernels where calculated for the measurement and a priori covariances of the TES nadir retrieval, the MIPAS retrievals and a joint retrieval using Eq.8 [Rodgers 2000]. These show that as expected the TES averaging kernels are broader than those for MIPAS, which mean that for a given altitude the information contributing to the TES retrieval is coming from a broad range of altitudes whereas for the MIPAS retrieval the information contributing to the retrieval is mostly coming from the retrieval altitude.

$$\mathbf{A} = \mathbf{I} - (\mathbf{S}_x \mathbf{S}_a^{-1}) \tag{8}$$

Where $\mathbf{S}_x$ and $\mathbf{S}_a$ are the covariances of the state vector and the *a priori* respectively, $\mathbf{A}$ is the averaging kernel and $\mathbf{I}$ is the identity matrix.

The number independent pieces of information were also calculated for the measurement and *a priori* covariances of the TES nadir retrieval, the MIPAS retrievals and a joint retrieval using Eq.9 [Rodgers 2000] .

$$\text{Number of independent pieces of information} = \text{Trace}(\mathbf{A}) \tag{9}$$

This showed that MIPAS had a larger number of independent pieces of information contributing to the retrieval than the TES in this case. The number independent pieces of information did increase for the combined retrieval but not by as much as expected. This again indicates that there is more information available in the selected microwindows for the stratospheric region than there is for the tropospheric region.

## 6. CONCLUSIONS AND FUTURE WORK

The retrieved ozone and temperature profile using the TES nadir retrieval show that there needs to be further work done on the TES nadir retrieval before it can be combined with the MIPAS measurements. These results, along with the analysis of the averaging kernels and the independent pieces of information, indicated that the microwindows selected for the TES nadir retrievals are not as suitable for a joint retrievals; therefore a new set of microwindows needs to be selected for the joint retrieval.

The current microwindow selection considers the information content relative to the *a priori*, which in this case was the climatology, for all altitudes and selected the microwindows with the largest total information content for all retrieved species combined. The analysis of the averaging kernels indicates that most of the information contained in the microwindows comes from the stratosphere and that the microwindows selected only contain a small amount of information from the troposphere, which is not sufficient for good tropospheric retrievals of ozone and temperature.

To improve the TES nadir retrieval a larger number of microwindows will be selected to increase the tropospheric information available for the retrieval. The TES nadir retrievals can then be combined with the MIPAS retrieval using a specially selected set of microwindows for the combined retrieval. This new set of microwindows will be selected based on the information content of the microwindows relative to the MIPAS retrievals instead of the climatology.

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