Technical Note on

Implementation of balloon geometry option and MIPAS-B data analysis

Draft

Delivery of WPs 4500- 6700 of the CCN#2 of the study:
"Development of an Optimised Algorithm for Routine p, T and VMR Retrieval from MIPAS Limb Emission Spectra"
Contract no.: 11717/95/NL/CN

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1. Reference documents

[R1] Friedl-Vallon, G. Maucher, O. Trieschmann and H. Oelhaf , 'MIPAS-B-Flight Report: Flight #6 of 7/8.5.98 from Aire sur l'Adour / France' - Rev.1 (22.12.1999).

[R2] O. Trieschmann, 'Level 0 to 1b Data Processing of the MIPAS-B2 balloon borne Fourier Transform Spectrometer', Draft version (February 1998).

[R3] M Ridolfi, B. Carli, M. Carlotti, T. von Clarmann, B. M. Dinelli, A. Dudhia, J.-M. Flaud, M. Höpfner, P. E. Morris, P. Raspollini, G. Stiller, and R. J. Wells, "Optimized forward model and retrieval scheme for MIPAS near-real-time data processing", *Applied Optics*, **39**, (2000).

[R4] Proposal of CCN2 of Contract 11717/95/NL/CN, 'Consolidation of Performance Critical Mipas Level 2 Functionalities and Pre-Flight Validation'

[R5] M. Carlotti, private communication, Delivery of Bologna Occupation Matrix Algorithm (BOMA), e-mail of 11 Nov 1998

2. Introduction

The infrared emission limb sounder MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) will be operated as an ESA core instrument on the ENVISAT-1 satellite. Near real time retrieval of pressure, temperature (p, T) and volume mixing ratio (VMR) profiles of six key species (O_3, H_2O, N_2O, CH_4 and HNO_3) from MIPAS calibrated spectra will be performed in the Level 2 processor of the ENVISAT payload data segment.

An Optimised Retrieval Model (ORM) has been developed for near real-time retrievals as part of the present ESA-supported study [R3]. The code has been completed and delivered to ESA for industrial implementation. The code has been validated performing test retrievals from spectra generated by both the OFM (Optimised Forward Model) developed at IROE, and the RFM (Reference Forward Model) developed at University of Oxford. These numerical tests provided consistent results confirming the correct operation of the code.

Nevertheless, the complexity of the analysis involved, the possibility of encountering unexpected errors introduced either by the instrument or by the Level 1b processing, the novelty of the adopted technical solutions and the novelty of the measurements (e.g.: use of emission measurements, new Microwindow selection) recommend that some experimental tests are made with real data.

To this purpose measurements obtained from a balloon borne platform with an instrument built at IMK, which is named MIPAS-B and is very similar to the satellite instrument, have been analysed with the ORM code. The present Technical Note provides the results of this test exercise.

The report of the balloon flight performed with the MIPAS-B instrument is provided in [R1].The raw measurements of MIPAS-B have been calibrated and characterised with a processor that is similar to the one that will be performed in the Level 1b analysis of the satellite instrument. This analysis is described in [R2]. The calibrated and characterised spectra are the inputs of the ORM.

The present Technical Note reports on the modifications that have been introduced in the ORM code in order to analyse measurements obtained from an instrument located inside the atmosphere, and presents the results of the retrievals together with a critical discussion of some relevant tests.

The retrieval exercise has involved the investigation of many possibilities and hypotheses that are not reported here in their tedious sequence of exploratory operations. On the basis of the final results, only those tests that are needed to support the conclusions are presented and discussed here.

3. Objectives of the technical note

Objectives of the present technical note are:

- to report the modifications that have been introduced in the ORM code in order to analyse measurements obtained by an instrument located inside the atmosphere which therefore opertes with a different observation geometry
- to present the results of the ORM retrievals from balloon measurements, together with a critical discussion
- to comment about the lesson that this test exercise provides for MIPAS near real time ORM retrievals

4. Modifications introduced in the satellite version of the ORM

The main difference between balloon and satellite measurements is that the balloon flies in the stratosphere while the satellite flies at a large distance from the Earth, outside the atmosphere. This implies that some of the choices adopted as a baseline for the ORM code, developed for the analysis of satellite measurements, cannot be applied to the analysis of balloon measurements. In the ORM these choices are:

- each measurement is characterised by a single parameter, i.e. the tangent altitude;
- the Field of View (FOV) angular response of the measurements can be parameterised in the altitude domain by a tangent altitude independent distribution;
- the optical path is symmetric with respect to the tangent altitude point and the radiative transfer calculations can exploit this symmetry in order to save computing time.

These choices cannot be used in the case of balloon observations and the alternative solutions adopted in this case are described in the subsequent sub-sections.
The balloon version of the ORM will be indicated in the following with the acronym ORM_BA.

Apart from the differences arising from the different location of the satellite and the balloon instruments, the ORM_BA code uses all the optimisations implemented in the ORM_ABC code, in order to test the performance of the on-line processor of MIPAS satellite instrument with data acquired experimentally by an instrument that is operating inside the atmosphere.

4.1 – Ray-tracing

Since in the case of balloon observations also up-looking measurements can be performed, in which the tangent altitude point is not reached, ORM_BA version uses the pointing angles and the balloon flight altitude (that is not constant with time) for the identification of the observation geometry. Tangent altitudes, computed using the pointing angle and the balloon flight altitude relative to each down-looking spectrum, are only used internally to the code, to maintain consistency with the satellite version of the ORM (the profile retrieval is still performed in correspondence of the tangent altitude of the measurements). The pointing angles are expressed as Zenith Limb Scanning (ZLS) angles. The ZLS angle is the angle between the line of sight of the instrument and the line that joins the instrument position with the Earth's centre (see Fig. 1).
Accordingly, the FOV is defined in terms of angular distribution around the nominal ZLS angle of each measurement.

The stratification of the atmosphere used to compute the radiative transfer integral is built starting from an altitude grid that includes the retrieval grid, i.e. the grid of the tangent altitudes, and the average flight altitude.

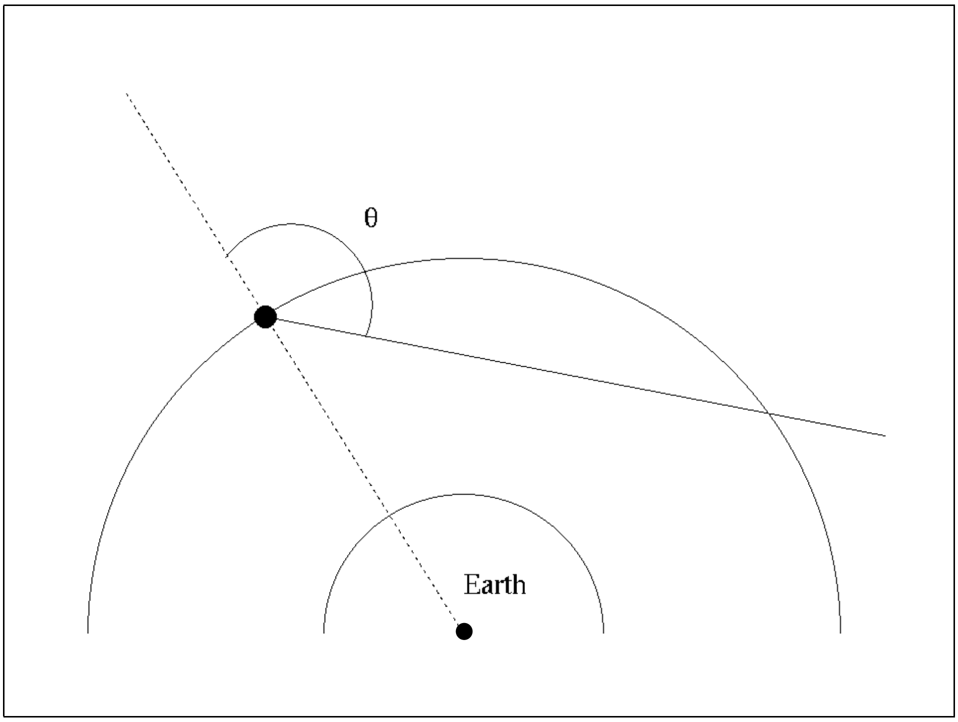


Figure 1: Definition of Zenith Limb Scanning angle (θ)

4.2 – Radiative transfer

The optimised radiative transfer equation used in the ORM_ABC [R3] is equal to:

$$S_{\sigma,g} = \sum_{l=1}^{L} B_\sigma\left(T_l^e\right)\cdot\left(1-\tau_{\sigma,l,g}\right)\cdot\left(1+\tau_{\sigma,l,g}\cdot\prod_{j=l+1}^{L}\tau_{\sigma,j,g}^2\right)\cdot\prod_{j=1}^{l-1}\tau_{\sigma,j,g}$$

where the summation is performed only over the layers of the descending leg of the line of sight. This formula exploits the symmetry of the line of sight with respect to the tangent point.

In the ORM_BA code, the radiative transfer calculation is made by determining sequentially the contributions of both the descending and of the ascending legs of line of sight with the following expression:

$$S_{\sigma,g} = \sum_{l=1}^{N} B_\sigma\left(T_{l,g}^{e\,\mathrm{main}}(z)\right)\cdot\left(1-\tau_{\sigma,l,g}\right)\cdot\prod_{j=1}^{l-1}\tau_{\sigma,j,g} .$$

in which the summation is extended to the layers of both legs.

4.3 – Field of view (FOV) convolution

While in the case of satellite geometry a given angular aperture corresponds to an approximately constant vertical aperture, in the case of balloon geometry the vertical aperture varies quite dramatically with tangent altitude, as reported in Table 1.

Table 1: Vertical aperture (in km) of the FOV for satellite and balloon geometries. For the satellite case, the angular aperture and the satellite flight altitude are assumed to be respectively 0.070 deg and 800 km. For the balloon case, an angular aperture of 0.2834 deg and a balloon flight altitude of 38.5 km are used.

Tangent altitude (km)	Vertical FOV (km) for satellite geometry	Vertical FOV (km) for balloon geometry
53.0	3.89	
50.0	3.90	
47.0	3.91	
44.0	3.91	
41.0	3.92	
38.0	3.93	0.40
35.0	3.94	1.05
32.0	3.94	1.43
29.0	3.95	1.72
26.0	3.96	1.98
23.0	3.97	2.20
20.0	3.97	2.41
17.0	3.98	2.59
14.0	3.99	2.77
11.0	3.99	2.93
8.0	4.00	3.09

For balloon measurement the FOV function is expressed by an analytical distribution. In order to comply with the fact that the instrumental FOV is no longer constant with altitude, the distribution is given as a function of the angular displacement from the central direction instead of as a function of tangent altitude differences. In the ORM_BA, as in the ORM_ABC code, the FOV effect is modelled with an analytical convolution of the FOV with the interpolated spectrum. A difference is that, while in the satellite version the interpolation is made in the altitude domain, in the balloon version the interpolation is made in the ZLS angle domain.

4.4 – Other differences between ORM_ABC and ORM_BA

In this section we list other minor differences between the satellite and the balloon ORM versions.

Balloon spectra have been recorded at a smaller spectral resolution than the satellite spectra. This is taken into account by the AILS (provided by IMK) and requires in the ORM some settings and changes in the calculation of the measurement VCM (Variance Covariance Matrix). The settings involve the parameters that calculate the correlation which in this case are due both to the spectral oversampling and to the apodization. The changes refer to the calculation of the variance since the NESR calculated by IMK refer to the apodized zerofilled spectrum while ORM is programmed to use that of the unapodized spectrum with no zero-filling.

In both the ORM_ABC and the ORM_BA the unknown profiles are retrieved as a function of pressure, that is used as the variable of the altitude domain. Furthermore, values are retrieved in correspondence of the tangent altitude points that are identified by their tangent pressures.
Since in the case of balloon measurements some measured spectra correspond to up-looking observations, for which a tangent point is not defined, in ORM_BA the number of fitted points is in this case smaller than the number of measured spectra.

The expression of the derivatives of the spectra with respect to VMR and continuum parameters has been changed with respect to the ORM_ABC code as a consequence of the different expressions used for the radiative transfer equation in the two programs (see Sect. 4.2). The modified expressions are, respectively:

$$\frac{dS_{\sigma,g}}{dVMR_i}=\sum_{l=1}^{N}B\left(T_l^{e,main}\right)\cdot\left(\sum_{j=1}^{l-1}kj\,\frac{-dC_j}{dVMR_i}-\tau_{\sigma,l,g}\sum_{j=1}^{l}kj\,\frac{-dC_j}{dVMR_i}\right)\cdot\prod_{j=1}^{l-1}\tau_{\sigma,j,g}$$

$$\frac{dS_{\sigma,g}}{dk_i^{contret}}=\sum_{l=1}^{N}B_l\left(T_l^{e}\right)\cdot\left(\sum_{j=1}^{l-1}C_j^{air}\,\frac{-dk_j^{cont}}{dk_i^{contret}}-\tau_{\sigma,l,g}\sum_{j=1}^{l}C_j^{air}\,\frac{-dk_j^{cont}}{dk_i^{contret}}\right)\cdot\prod_{j=1}^{l-1}\tau_{\sigma,j,g}$$

In ORM_BA code the derivatives with respect to the tangent pressures are calculated only for the spectra with ZLS angles ≥ 90 (for the others a tangent pressure cannot be defined)

In the p,T retrieval we determine the tangent pressures values and the profile of temperature as a function of pressure. The hydrostatic equilibrium provides the relationship that associates the retrieved values of pressure and temperature with an altitude scale starting from a known value. Both the satellite code and the balloon code use the measured tangent altitude of the lowest limb measurement as a starting point of the altitude scale reconstructed with the hydrostatic equilibrium. The engineering measurements of the line of sight (LOS) provide further measurements of the tangent altitude and of the altitude increments between subsequent measurements. These increments, with their measurement error, can be used as the measurement of a function of the unknown p,T values: the function being the hydrostatic equilibrium relationship. If not otherwise specified p,T retrievals exploit the LOS information.

The original choice of using a fixed pressure value at the balloon flight altitude, instead of the balloon flight altitude itself, was eventually rejected, because it introduced a constrain that did not appear to be consistent wit the observation and furthermore because it introduced large differences between satellite and balloon retrievals. The possible alternative of using the balloon altitude as starting point of the altitude scale reconstructed with the hydrostatic equilibrium instead of the lowest tangent altitude was also discarded because of the differences with satellite retrievals.

It should be noted that some problems could arise from the fact that in the ORM_BA code both the lowest tangent altitude and the flight altitude are assumed to be fixed, making the altitude distance between the flight altitude and the lowest tangent altitude a constant parameter of the retrieval. This has no effect in the satellite retrieval, but may be a too strong constrain in balloon measurements in which the two altitudes are very close and are both inside the atmosphere (see Sect. 5.5).

4.6 – Retrieval setting

The Micro Windows used in the analysis have been selected from the measurements coming from all the four channels used by MIPAS-B:

Channel 1 – frequency range 685.0 – 969.975 cm^{-1}
Channel 2 – frequency range 1020.0 – 1499.975 cm^{-1}
Channel 3 – frequency range 1570.0 – 1749.975 cm^{-1}
Channel 4 – frequency range 1820.0 – 2409.975 cm^{-1}

The MWs selection has been made using the Bologna Occupation Matrix Algorithm [R5].

The measurement sequence is composed by 11 observation angles. For each observation angle 4 independent spectra have been measured.
Some preliminary test retrievals have been performed using a single measurement (these tests have only been made with data of channels 1 and 2). Since the average of the retrieved profiles from single sweeps was very similar to the profile retrieved from the averaged spectra, it has been decided to use the averaged spectra for all the retrievals.

Tests have been made using or not using the Marquardt damping factor λ in the last iteration and the final choice has been in favour of using the damping factor also in the last iteration. The final Estimated Standard Deviation (ESD) of the retrieved profile is calculated without the damping factor.

Tests have been made for the p,T retrieval to determine the best value of the Marquardt damping factor λ, and the best choice is 0.1

Two different convergence criteria have been tested:
1. Maximum difference allowed between calculated χ^2 and linear χ^2 (18% p,T; 5% VMR)
2. Maximum difference allowed between the actual χ^2 and the χ^2 of the previous iteration (2%).

The final choice has been to use the second criterion.

5. - Analysis of IMK balloon measurements with ORM

5.1 – P,T results of early retrievals

The analysis of IMK balloon measurements has been a very long process and only a summary of results is here reported, with examples limited to those retrievals that provide important evidence for the conclusions.
Early retrievals gave very large values of chi-square and different results for different occupation matrices. Furthermore, unsatisfactory results were obtained when comparing the tangent altitudes determined with the hydrostatic equilibrium with those measured as part of the engineering data. This comparison is considered to be an important check of internal consistency since the pointing of the measurements is very well known (the 3σ error on the pointing angle is 1 arcmin).
In this section all our consideration will be concentrated on p,T retrieval results because of the important internal consistency test of altitude correction that is available in this case and because of the consequences that this retrieval has on VMR retrievals.
An example of the typical results that have been obtained in p,T retrievals (after the solution of the preliminary technical problems that are not discussed here) is provided by Figures 2, 3 and 4, that show respectively the comparison between initial guess and retrieved value for temperature, the altitude correction and an histogram of the chi-square values for each MW.

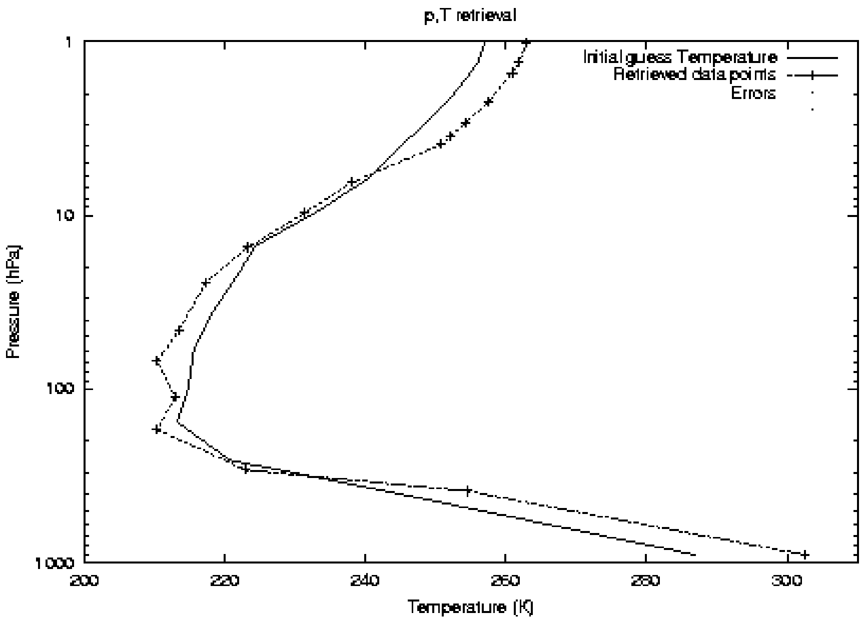


Figura 2 Retrieved temperature profile in early retrieval

The occupation matrix used for this retrieval was determined using BOMA with the following criteria:

- the cpu time was neglected
- all spectral channels were used

The results show :

- very large χ^2 values that make the total χ^2 of the retrieval equal to about 35

- large tangent height corrections despite the very small estimated error of altitude retrieval (30-40 meters)

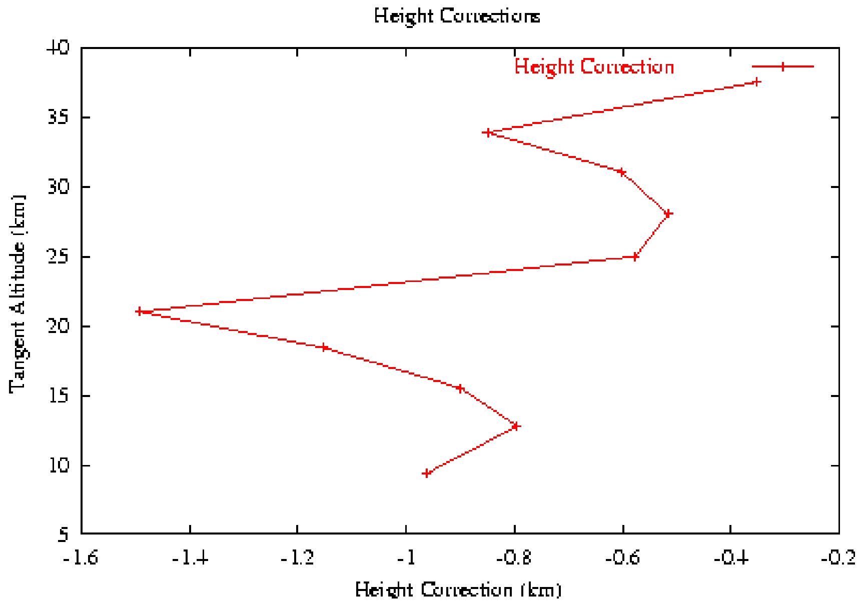


Figure 3 Tangent altitude correction in early retrievals

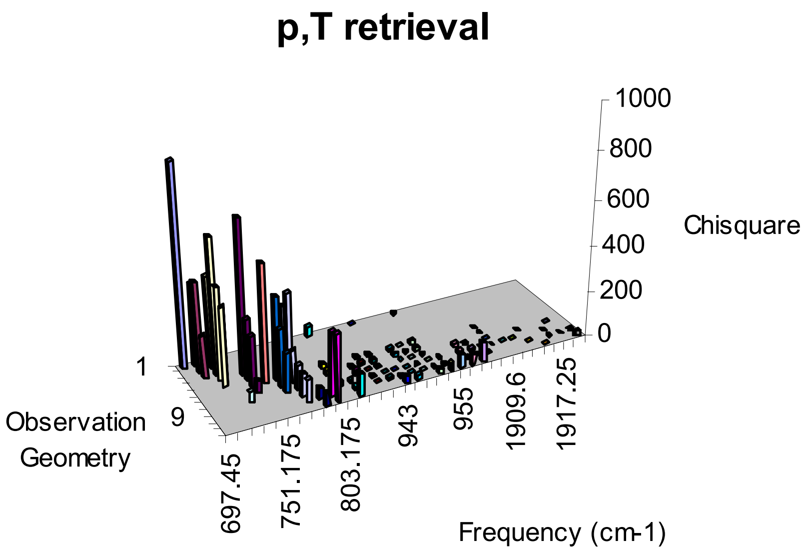


Figure 4 Individual X^2 values in early retrievals

The retrieval error of pressure and temperature is clearly underestimated because the χ^2 value is very large, but still these altitude correction are not acceptable.

We notice in Fig.4 that the χ^2 values of the MWs of the first channel are very large in comparison with the others. On the basis of this consideration we have performed for a comparison retrievals with a new OM that did not include MW of the first channel and with a new OM that used only MW of the first channel.

When MW of the first channel are not used the total χ^2 value of the retrieval is reduced to the very reasonable value of 1.5, and the altitude error is smaller (about 500 metres with a retrieval error of 70 metres)

Figures 5 and 6 show a comparison among the results obtained using the three different OM for retrieved temperature and altitude correction respectively.

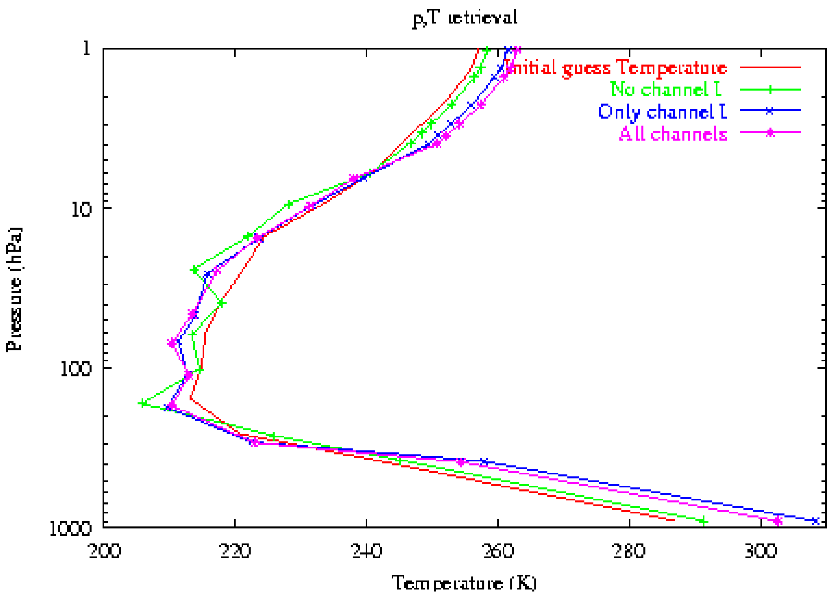


Figure 5 Comparison of temperature profiles retrieved with different OMs

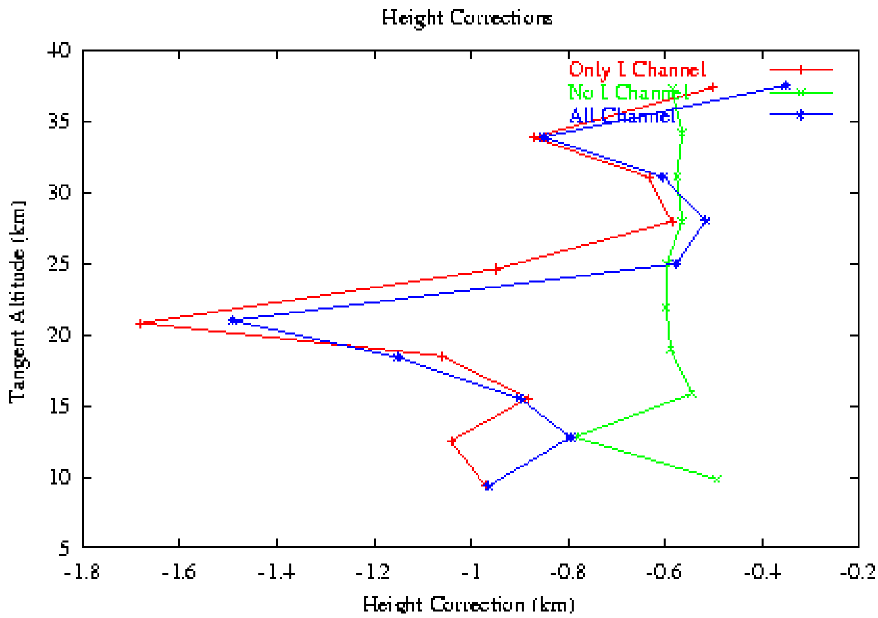


Figure 6 Comparison of tangent altitude corrections with different OMs

The ESD (the retrieval error) is smallest when we use MWs of the first channel, while the total χ^2 value and the altitude difference is smallest when we do not use MWs of the first channel.

The effect of MWs of the first channel on the χ^2 value is a clear direct effect, but the effect on altitude difference could also be an indirect effect induced by changes in the ESD that change the relative weight between retrieval information and LOS information.

The outstanding problems in the early p,T retrieval are:

- large values of chi-square in the MWs below 820 cm-1
- large tangent altitude correction (OM dependent when LOS information is used)

Possible causes of the problem are:

1. errors in the processes of the ORM_BA code
2. errors in the setting of the ORM_BA code
3. errors in the input data caused by the balloon instrument
4. errors in the input data caused by the level 1b processing
5. errors in the parameters that are used as constants by the code.

The identification of these errors may be made difficult by the fact that when a few different errors are present at the same time their combined effect can be very complicated and it is difficult to disentangle the feature observed in sensitivity tests. These five types of errors have all been critically analysed

1. To validate the processes of the ORM_BA code, a new forward model code was developed and tested against the forward model code of the satellite. The ORM_BA was then used to perform several test retrievals on synthetic spectra generated by the new forward model. The correctness of the retrieval code was verified. In particular, in the case of p,T retrieval it was found that the corrections on tangent altitudes were few meters.
2. The Marquardt lambda value used for the parameters of the atmospheric continuum turned out to be set at a too large value (left from previous tests), causing difficulties in the fit of the continuum of low altitude spectra in the early retrievals
3. Water vapour inside the instrument was found to cause calibration problems in the case of strong lines. A set of critical transitions where identified by IMK and the OM selection was accordingly revised rejecting one MW.
4. A critical review has been made of the input parameters provided by level 1b (radiometric and frequency calibration, FOV and AILS, NESR, LOS) and sensitivity tests have been made varying some of these parameters (see Sect 5.4).
5. Spectroscopic errors have been identified as a critical error source, also considering that the balloon spectra have a NESR that is significantly better than that of satellite measurements (see Sect 5.3).

A few other specific facts have also been considered. They are:

- The MW's quantifiers were calculated for satellite observations and not balloon observations and so they may be not good for the balloon data retrieval
- OM's algorithm chooses too few MWs at some tangent altitudes, this could introduce some discontinuities in the retrieval and make difficult the determination of the instrumental continuum of those microwindows
- LUTs and irregular grids have been calculated for the NESR of satellite measurements and their approximations could become significant in the case of the better NESR of the balloon measurements
- Correlation introduced by apodization and zero-filling processes could not be handled in the ORM code consistently with the measuring procedure.

- because of both the lower spectral resolution and the better signal-to-noise ratio, in the case of balloon measurements the frequency width of the apodization function and of the MW extension should have been made larger
- Channel 1 has a calibration error that is expected to be larger than the other three, but in any case not larger than 1 or 2 %
- A small error was reported by IMK in the definition of the AILS for channel 3 (very few MW are located in channel 3).

However none of these specific facts was found to explain the large inconsistencies that have been observed in the retrievals .

5.2 - P,T reference retrieval

In the light of the considerations discussed in the previous section a few modifications have been introduced to the set-up of the retrieval. In particular:

- the value of Marquardt lambda used in for the parameters of the atmospheric continuum has been tuned in order to allow a better determination of this quantity,
- the few MWs, that have been identified by IMK as having a poor calibration because of interfering lines inside the instruments, have been removed
- the OM has been modified with the extension of the selected MW to all allowed tangent altitudes

The retrieval has been performed using all channels and exploiting the LOS information for the hydrostatic equilibrium constraint.

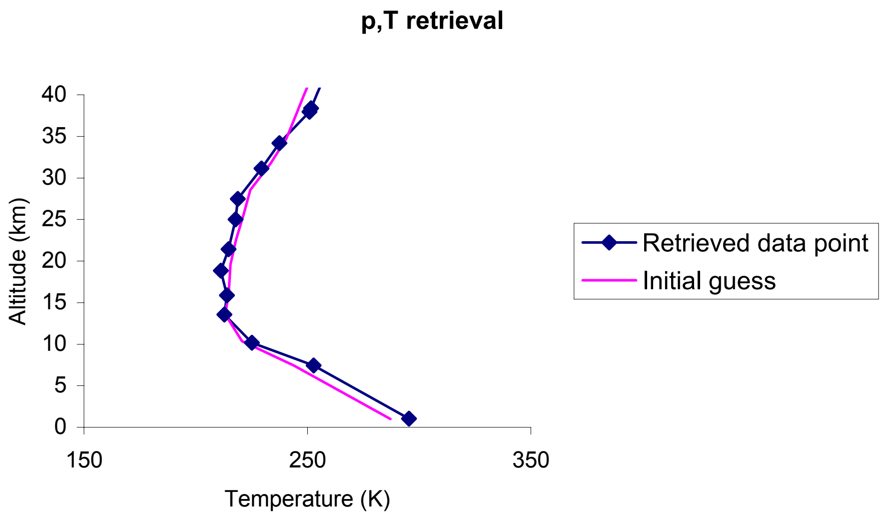


Figure 7 Retrieved temperature profile (reference case)

The comparison between initial guess and retrieved value for temperature, the altitude correction and the histogram of the chi-square values for each MW obtained with a retrieval made with this new OM are shown respectively in Fig.s 7, 8 and 9.
Large chi-square errors are still present, altitude errors are still large even if the shape has changed and the errors have been reduced at low altitudes as a consequence of the new lambda value. None of the implemented changes has removed therefore the main problems that affect the retrieval.

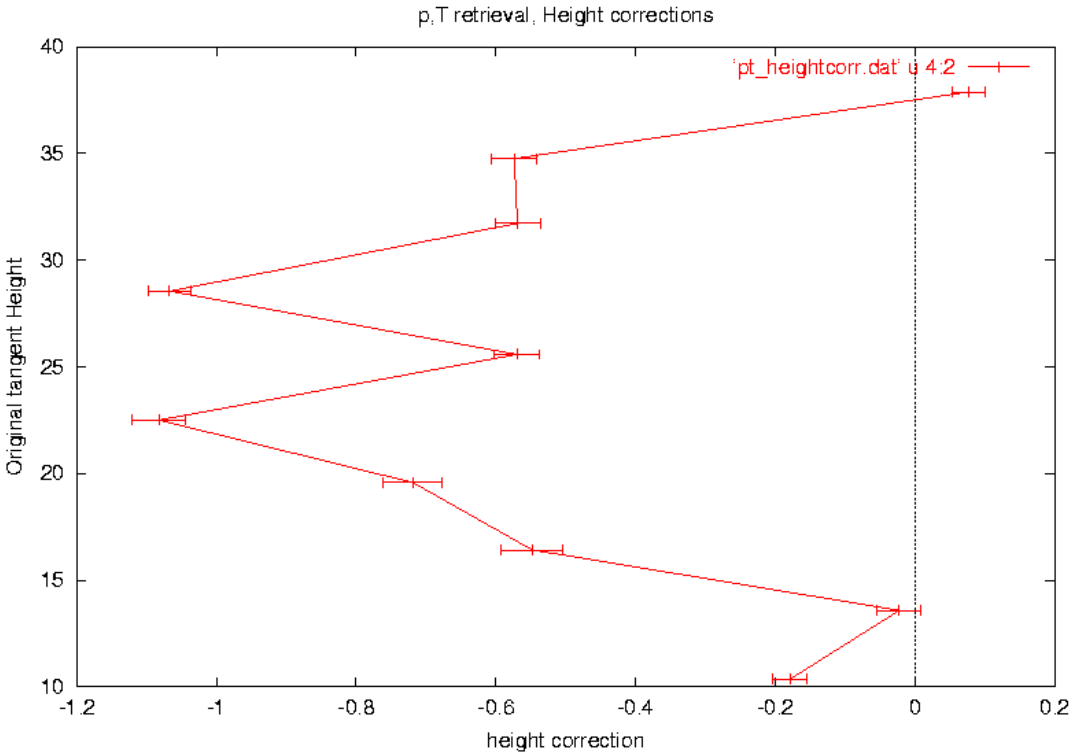


Figure 8 Tangent altitude corrections (reference case)

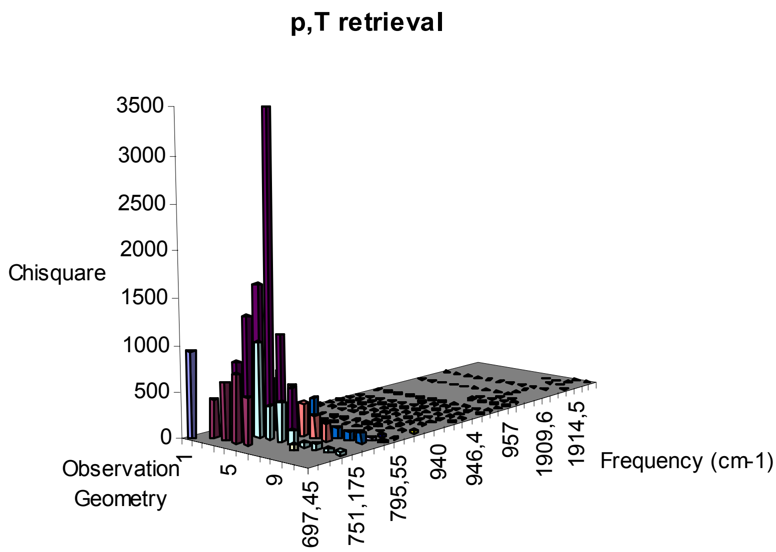


Figure 9 Individual X^2 values (reference case) (for the large X^2 values of the 4^{th} MW see Sect.5.5)

Nevertheless, this is an important retrieval because it is the most careful retrieval that we have been able to performs while conforming with all the input data that are provided to the ORM. This retrieval is used as a reference for the following test retrievals. In this test a problem is present in the X^2 values of the 4^{th} microwindow (see subsequent Fig.19 and related comments in Sect. 5.6), but this does not change the value as reference case of this retrieval.

5.3 – P,T retrieval considering spectroscopic errors

The residuals are much larger than the NESR in the MWs located at frequencies smaller than 820 cm^{-1}. From an inspection of these residuals we notice that these MWs are all characterised by strong signals and that the difference with the residuals at higher frequency would be smaller if expressed in percent value. This evidence seems to be consistent with the fact that the balloon measurements have a NESR that is smaller than the satellite measurements so that percentage errors due to uncertainties in the spectroscopic parameters are expected to have a larger effect.

A retrieval has been performed with the same conditions of the reference retrieval presented in Sect. 4.2, but with a NESR modified according to the following rule. The NESR is equal to the greatest value between the experimental NESR and 2% of the highest radiance observed in the spectrum
The comparison between initial guess and retrieved value for temperature, the altitude correction and the histogram of the chi-square values for each MW obtained with a retrieval made with this new value of NESR are shown respectively in Fig.s 10, 11 and 12.

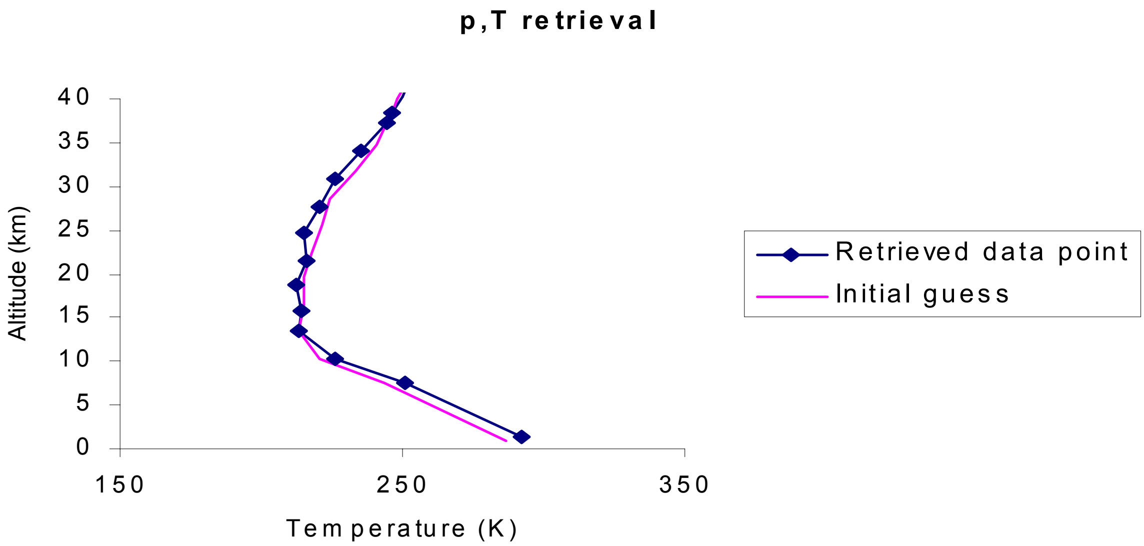


Figure 10 Retrieved temperature profile considering spectroscopic errors

The chi-square value is reduced from 35.0 to 4.5 proving that it is very reasonable to expect that spectroscopic errors contribute significantly to the observed residuals and our estimate of the NESR goes in the correct direction (the large error that is still present in the 4^{th} MW was later found to be due to a manual error, see Sect. 5.6). The error in altitude error has also changed shape as a consequence of the different weight given to different MWs, but the amplitude of the error is still large.
It could be argued that by changing the value of the NESR we have accounted for the amplitude of the spectroscopic errors, but we have not removed their systematic effects, therefore a systematic error in altitude determination is still possible.

This test has proved that the large chi-square values can be explained by the spectroscopic errors but has not removed the possibility that spectroscopic errors are also responsible of the altitude errors.

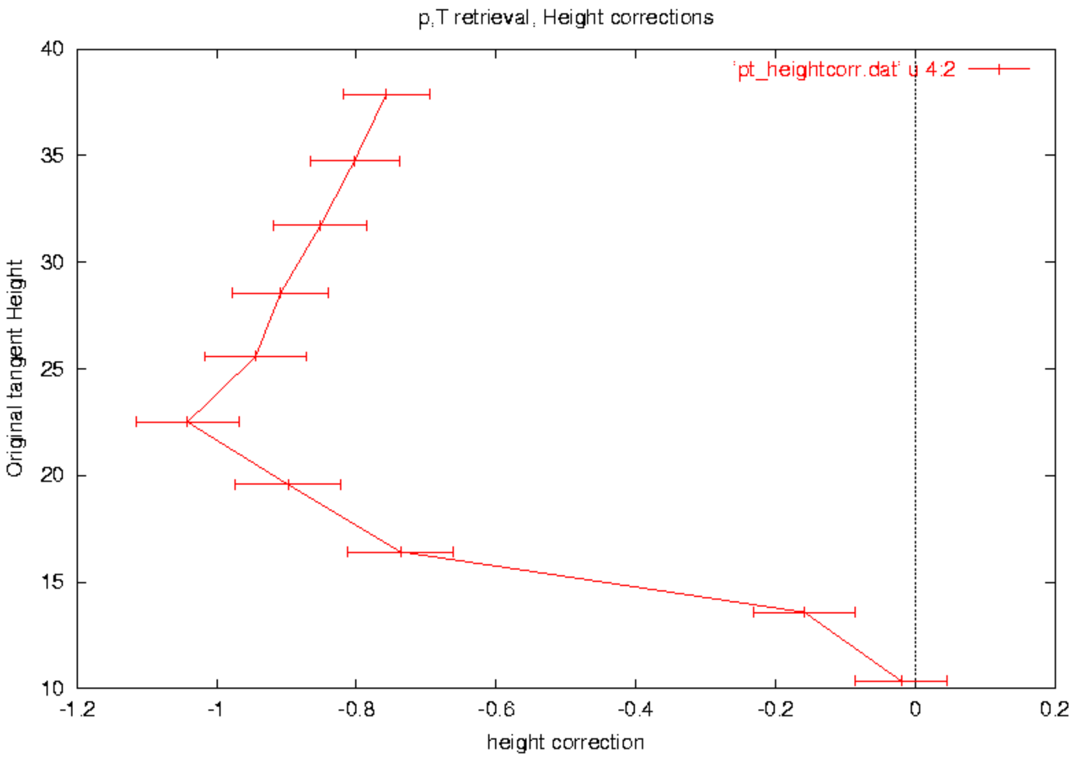


Figure 11 Altitude error corrections considering spectroscopic errors

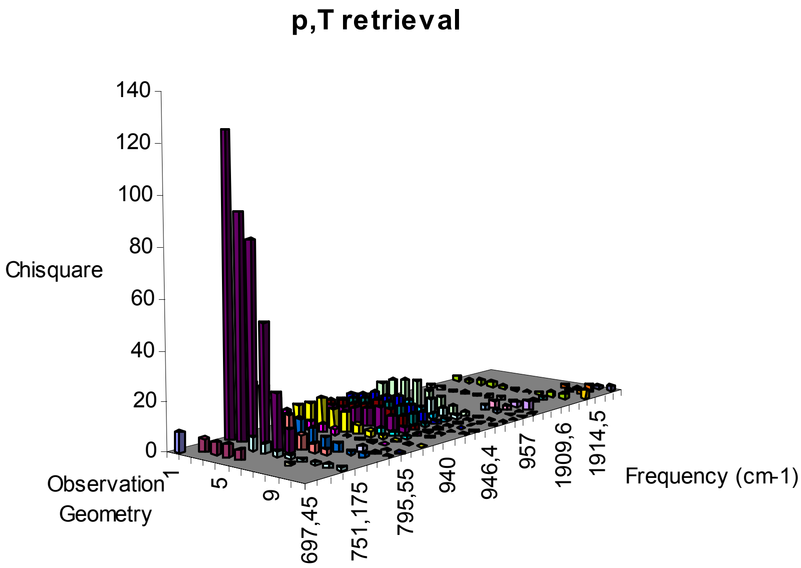


Figure 12 Individual X^2 values considering spectroscopic errors (for the large X^2 values of the 4th MW see Sect. 5.6)

5.4 – P,T retrieval search for the systematic error

In order to assess which systematic effect can have induced the bias in the retrieved value of altitude, a few sensitivity tests have been performed. In all these tests the NESR was modified to account for spectroscopic errors and one by one another input value was varied. The sign of the variation is always that which induces a reduction of the altitude difference. The following tests have been made:

- Test of calibration effects: the spectral intensity of the MWs of the first channel was increased by 3.5%. This is intended to simulate both calibration errors and line strength errors
- Test of pressure broadening effect: the pressure broadening coefficient of CO_2 lines was increased by 5%.
- Test on the AILS width: the AILS was slightly broadened by convolving the distribution provided by IMK with a three point function (0.05, 0.9, 0.05).

A further test consisted in assessing the effect of enforcing the measured values of tangent altitude:

- A-priory LOS information with very low error: in the VCM of the LOS information the flight altitude errors were reduced of a factor 5

The value of chi-square obtained for these five retrievals is compared in Table 2 with the values obtained in the reference retrieval and in the retrieval with enhanced NESR only. All these systematic biases, that tend to reduce the altitude difference, have in some cases a beneficial effect on the value of the chi-square, which is however small in comparison with the large effect that has been obtained by taking into account the spectroscopic errors.

Table 2: total X^2 values found in the different tests aimed to identify the presence of systematic errors

	Chi-square
Reference case	35.0
Spectr. Err. Case	4.5
Intensity err. Case	4.6
Pressure Broad. Case	3.9
LOS info. Case	4.7
AILS broadening case	4.0

In Fig. 13 a comparison of the tangent altitude corrections obtained in all these tests is shown. It is clear that (apart the obvious result obtained when reducing the error on the LOS information) a significant reduction of the altitude corrections is only obtained when the AILS is broadened. This result is apparently surprising when we consider that the variation that has been introduced is very small. Fig.14 shows the difference between the original and the broadened AILS. However the large sensitivity of the retrieval to the width of the AILS can be explained by the fact that the apodization process is masking the width of the ILS and significant variations in the width of the ILS may correspond to small variations in the width of the AILS. The relevance of the width of the ILS in the retrieval is well known.

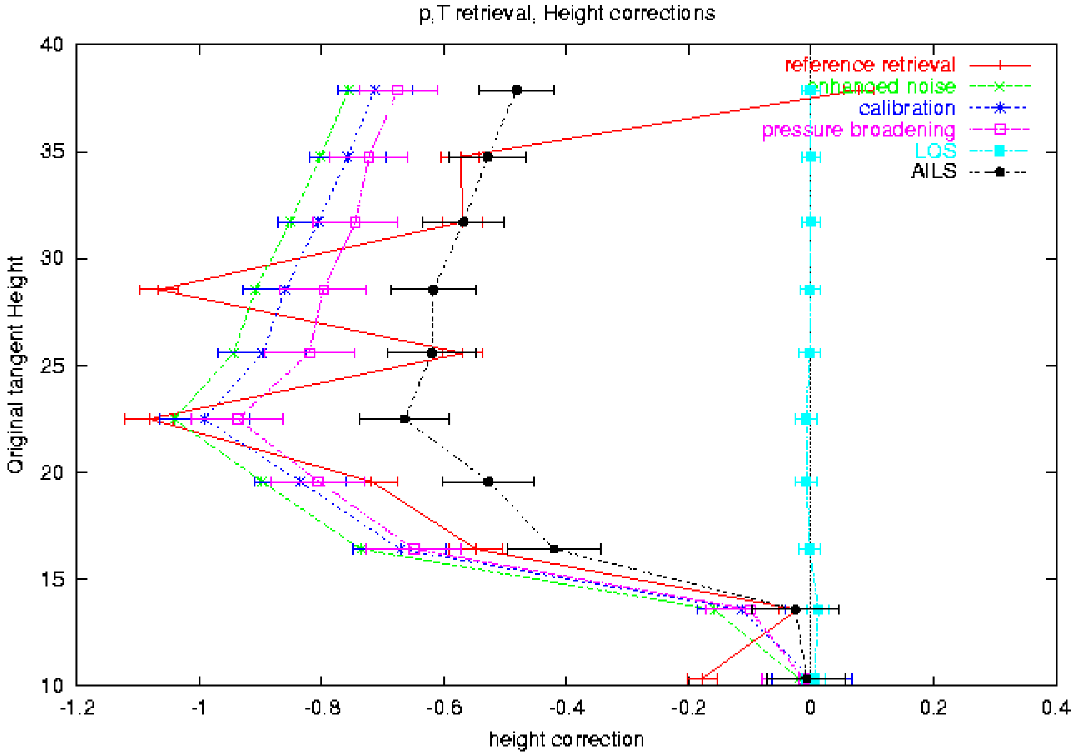


Figure 13 Comparison of tangent altitude corrections in the different tests aimed to identify the presence of systematic errors.

Fig. 15 shows a comparison of all retrieved temperatures plotted as difference relative to the initial guess. The temperature is affected by the different input parameters but the effect is relatively small when compared with the effect on altitude.

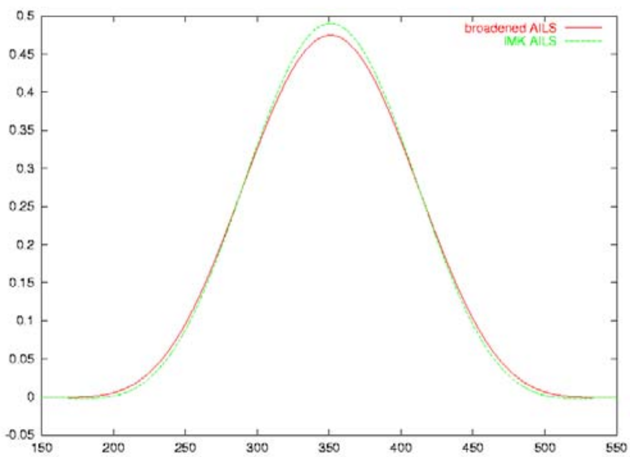


Figure 14 IMK AILS and broadened AILS as used in the test reported in Fig. 13

These results strongly suggest that the altitude offset may be related with our modelling of the instrument line shape. However up to now a weak point in the chain of data handling of this quantity has not been found. The AILS has been determined with high accuracy by IMK (quantitative numbers are to be evaluated), great care has been paid to the modelling of the reduced spectral resolution of the balloon measurements, the AILS convolution process of the ORM has undergone thorough tests.

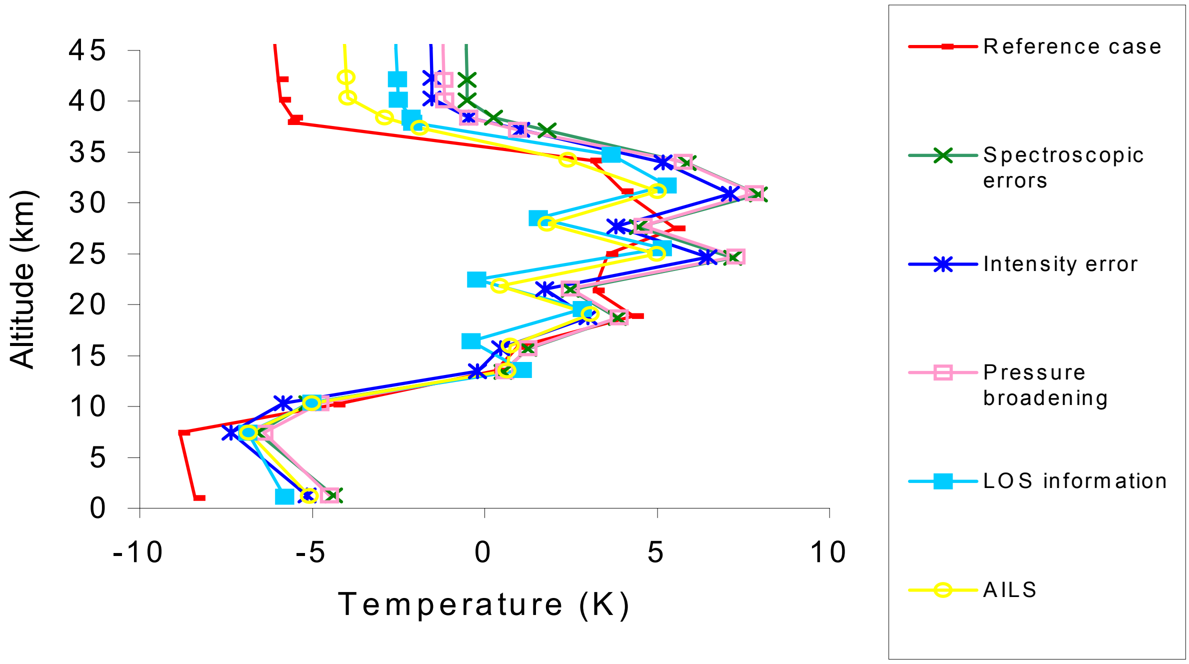


Figure 15 Deviation of the retrieved temperature profile from the initial guess profile found in the different tests aimed to identify the presence of systematic errors.

5.5 – Further tests

Figure 16 shows the comparison of the differences in altitude obtained in three retrievals made without the a-priory LOS information with different values of the lowest tangent altitude. This quantity was varied by adding and subtracting the nominal value the 3σ value of the pointing error. We notice that without the LOS information the spontaneous tendency of the retrieval is that of obtaining very large altitude offset and in this offset the contribution of the error that we can make in the determination of the lowest tangent altitude is very small. The X^2 values of these three tests are about 3.6. This test for assessing the effect of this parameter was made separately without LOS information because the lowest tangent altitude affect both the observation geometry and the reconstruction of the profiles with the hydrostatic equilibrium.

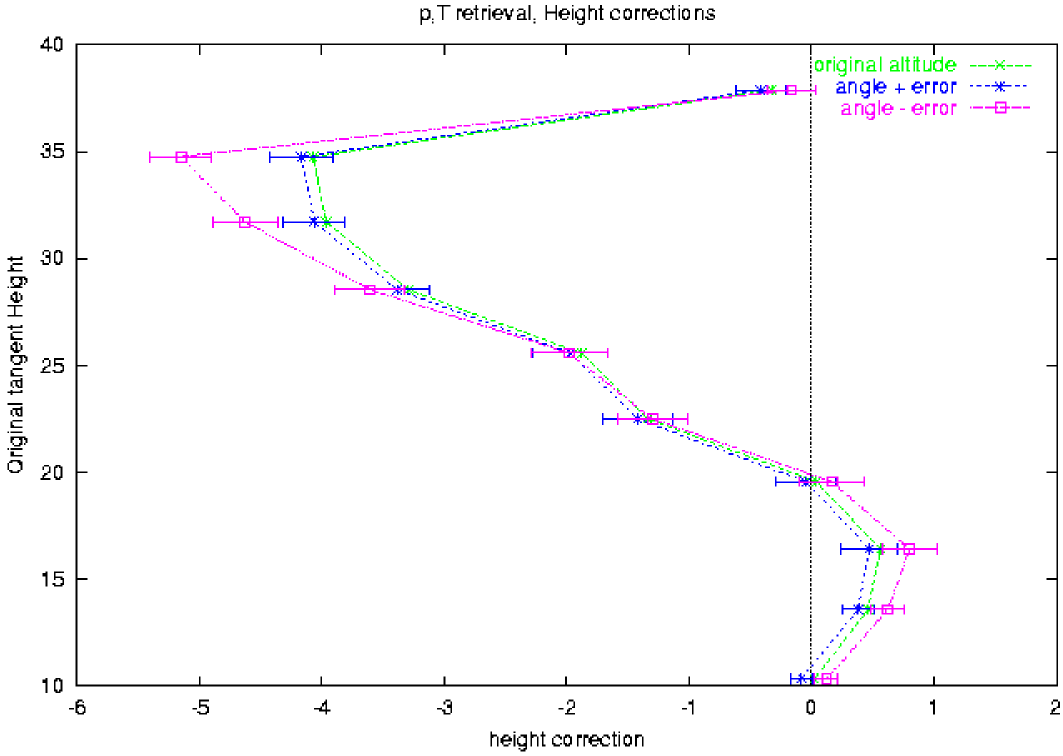


Figure 16 Effect of the value of the lowest tangent altitude on the tangent altitude correction. These results have been obtained without using the LOS information.

5.6 – Final p, T retrieval

We conclude that the only bias that can explain the offset in retrieved altitude is the AILS or associated operations. We do not know yet in which point of the chain an error has been introduced. While further tests are needed to solve this problem we need to identify the most reliable p,T retrieval which can be used as an input for VMR retrievals.
We believe that pointing information is more reliable than the modelling of the AILS, therefore, we built a retrieval with the following recipe:

- OM as in the reference retrieval
- NESR that takes into account spectroscopic errors (2% error is assumed)
- the AILS is broadened with convolution with a three point function (0.08, 0.84 , 0.08)
- use of LOS information with a VCM reduced by a factor 3.

Figure 17 shows the comparison of the temperature profile obtained by this retrieval with the temperature profile obtained independently by IMK and all the other profiles obtained in the previous tests. We notice that there is a correlation between the value of the temperature profile and the altitude correction. The profile obtained in this final retrieval and the IMK profile have very similar values which are not too different from the results obtained in the test in which altitude was forced to the measured value. These three retrievals are the ones with no altitude offset.
The altitude correction and the histogram of the chi-square values for each MW obtained with this retrieval are shown respectively in Fig.s 18 and 19. The total X^2 value for this retrieval is 3.1.

It has to be noted that in this final test retrieval the OM has been corrected in order to use the fourth microwindow only at the 'allowed' tangent altitudes. The cause of the large residuals at high altitudes was that this MW had been erroneously extended to altitudes that are not given as useful by the database. This correction has not been extended to the previous test retrievals because it does not change the retrieved values and only marginally affect the value of the total chi-square.

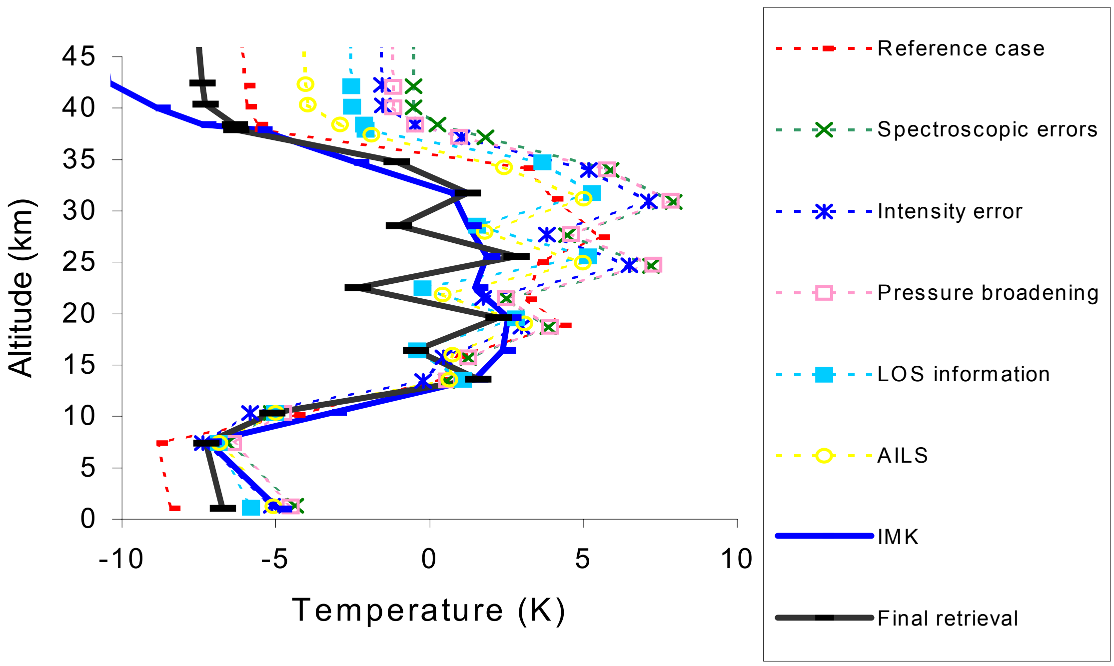


Figure 17 Deviation of the retrieved temperature profile from the initial guess profile in the final retrieval and comparison with the other test retrievals and IMK results.

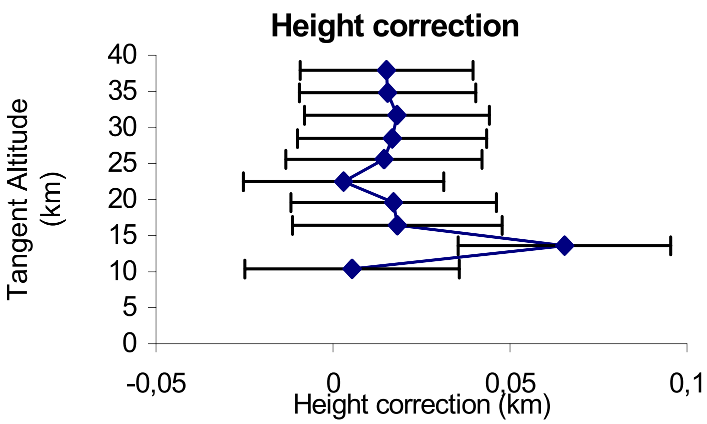


Figure 18 Tangent altitude correction in the final retrieval

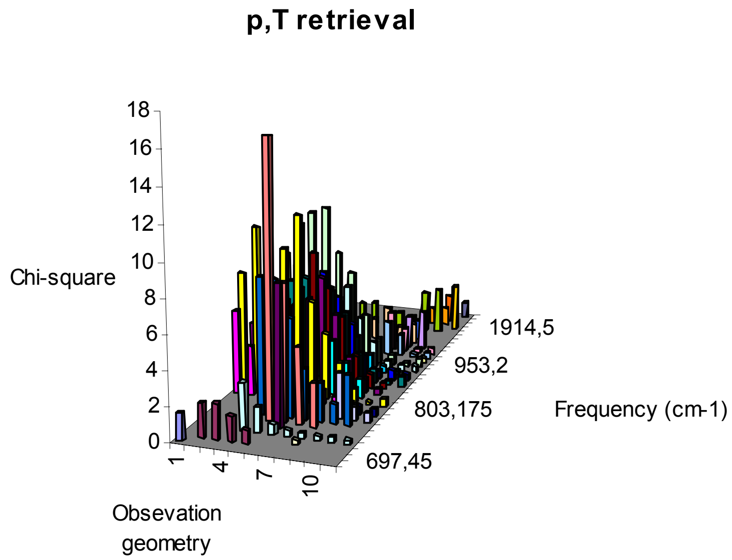


Figure 19 Individual X^2 values in the final retrieval (the corrected OM has been used, i.e. the MW no.4 is used only at the allowed tangent altitudes)

6 – VMR Retrievals

VMR retrievals have been performed with the following recipe :

- for each species an occupation matrix has been determined using the BOMA algorithm to select the MW from all channels of MIPAS balloon, the resulting OM has been manually extended to use for the selected MWs all the allowed altitudes
- the temperature profile and the tangent altitude of the retrieval presented in Sect. 5.6 have been used
- the AILS has been broadened by the convolution with a three point function (0.08, 0.84, 0.08)
- for each species two retrievals have been made one with the instrumental NESR and one with the NESR increased to account for possible 2% spectroscopic errors.

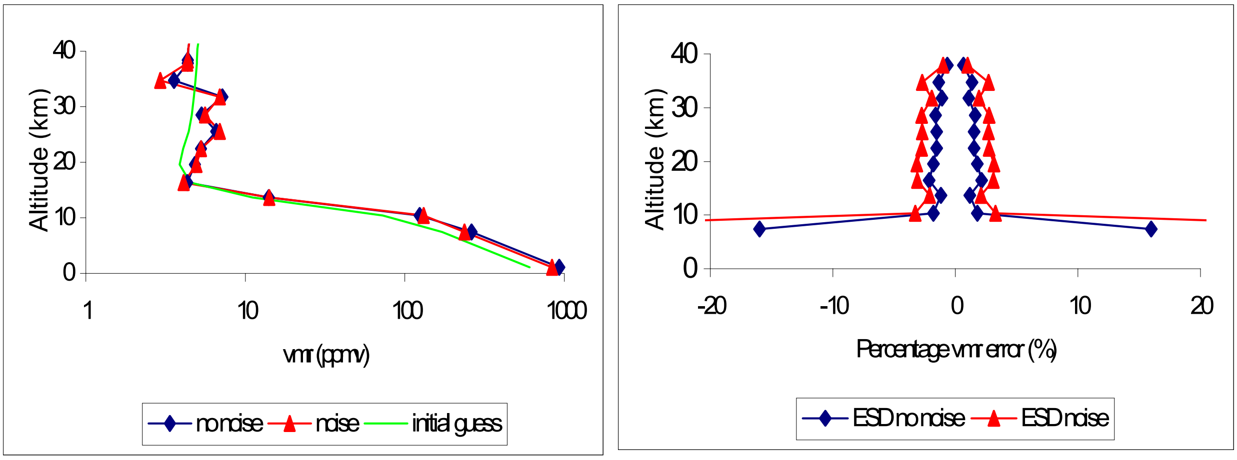
In the figures from 20 to 24 we show for each gas the profiles and the ESD that have been determined with the two retrievals and the histogram of the chi-square values that is obtained in the case of NESR corrected to account for spectroscopic errors.
The differences between the two retrievals are very small as far as the retrieved value is concerned and also the differences in ESD are not very large.
Table 3 shows a summary of the total chi-square value obtained for this set of retrievals confirming that the spectroscopic errors must be considered if a chi-square value closer to 1 is to be obtained.
Since the histograms of the chi-square values indicate that the largest residuals are often obtained at the highest altitudes in which the signal is small (less affected by spectroscopic errors) and more affected by the instrument line shape, some extra tests have been made for two species. In the cases of ozone and methane a retrieval has been made also without broadening the AILS. The total chi-square obtained in these two tests is reported in the last column of Table 3. Also for VMR retrievals more consistent results (smaller chi-square) are obtained with a broadened AILS.

We conclude that reasonable values have been obtained for the five species with chi-square values that, if we take into account the contribution of spectroscopic errors, are consistent with the expectations. Also VMR retrievals suggest a preference for a broader AILS.

The inspection of the residuals of the MWs with the largest residuals shows that some manual errors may still be present in some columns of the occupation matrix. Therefore the OMs can probably be improved, but this does not change the conclusions.

Table 3: total X^2 values in the different VMR retrievals

	IMK noise	Artificial noise	AILS not perturbed
H2O	4.5	2.0	
O3	256.1	6.1	7.7
HNO3	11.6	2.8	
CH4	31.7	5.4	7.8
N2O	19.0	7.6	



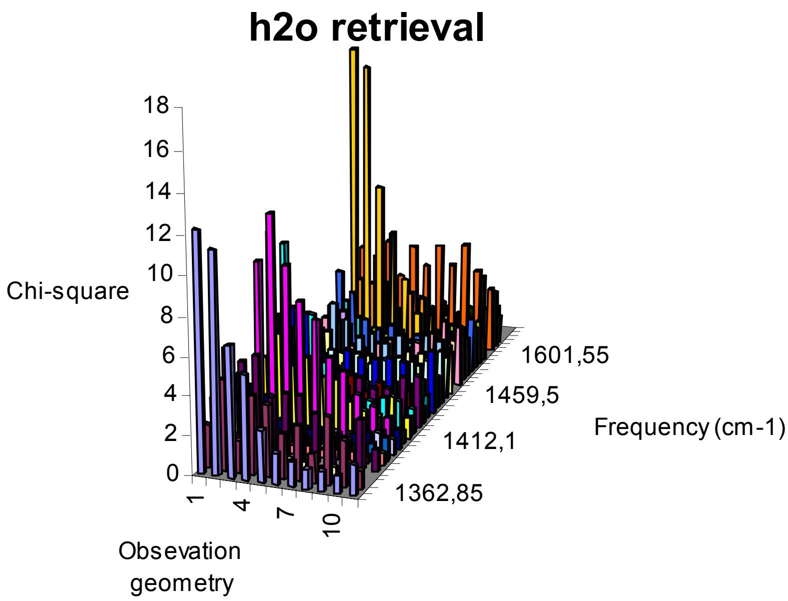
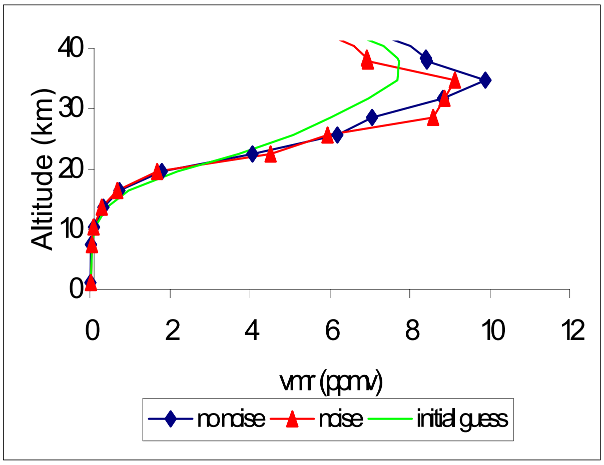
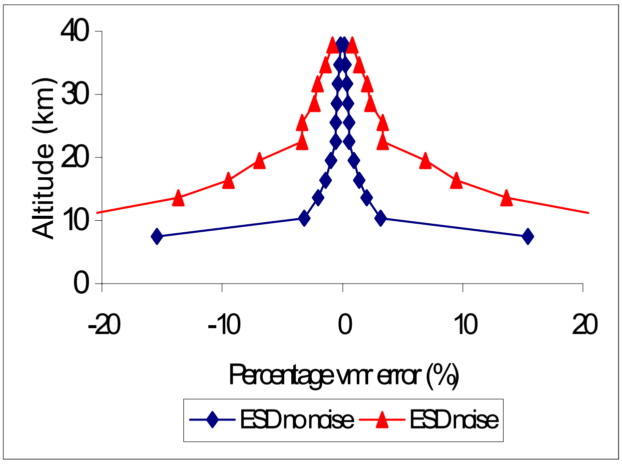


Figure 20 Results of H2O VMR retrievals





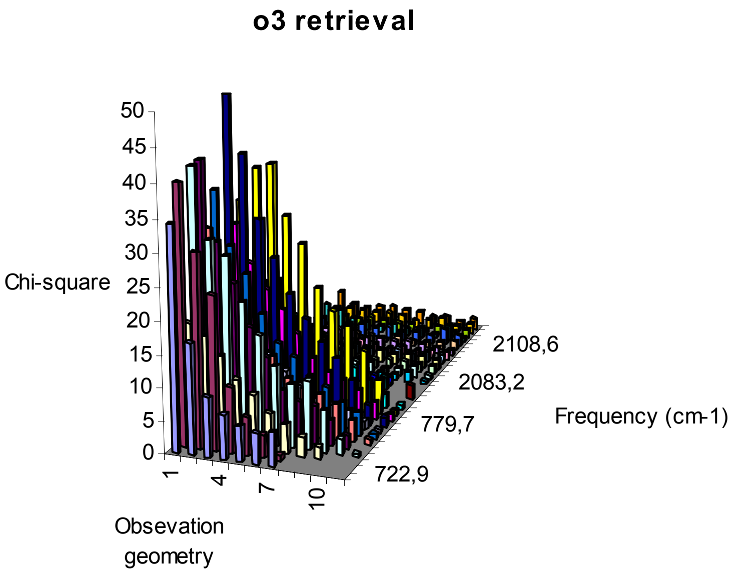
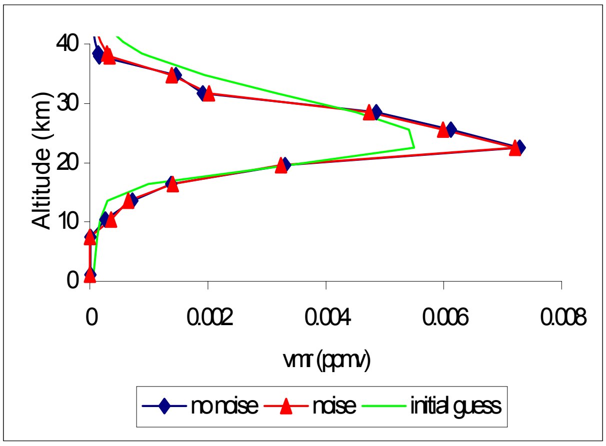
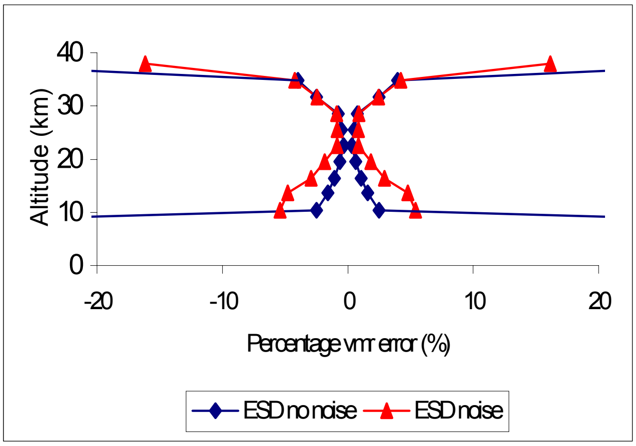


Figure 21 Results of O3 VMR retrievals





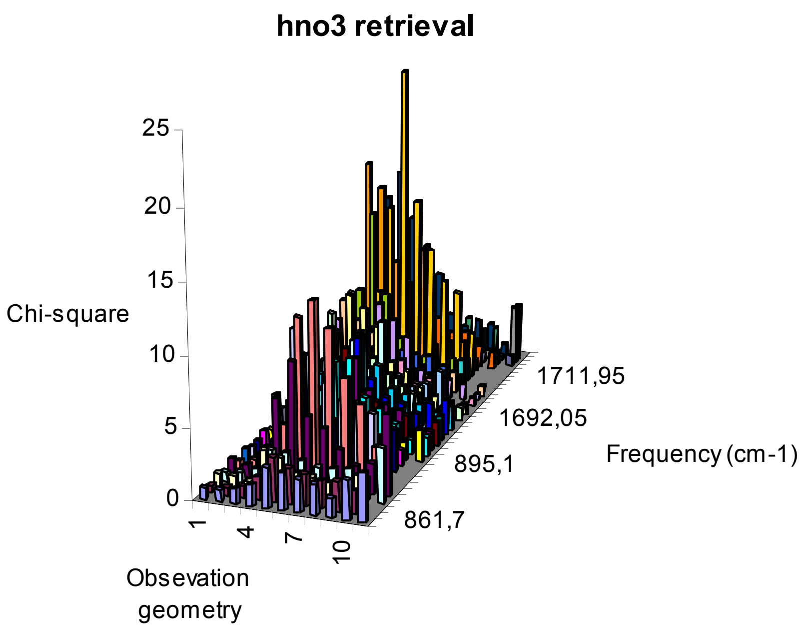
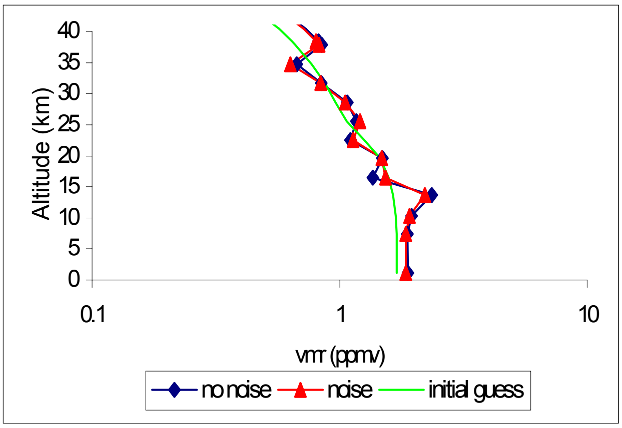
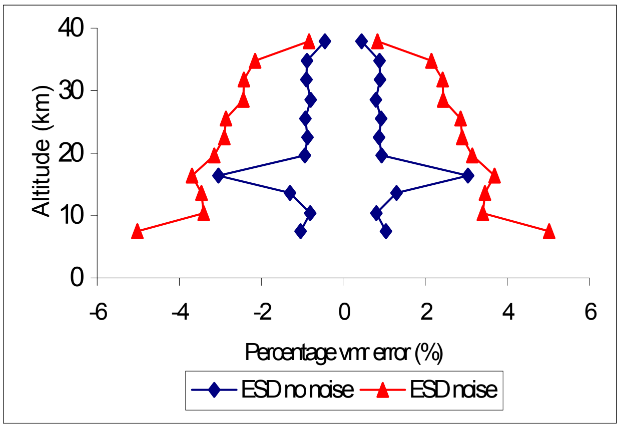


Figure 22 Results of HNO3 VMR retrievals





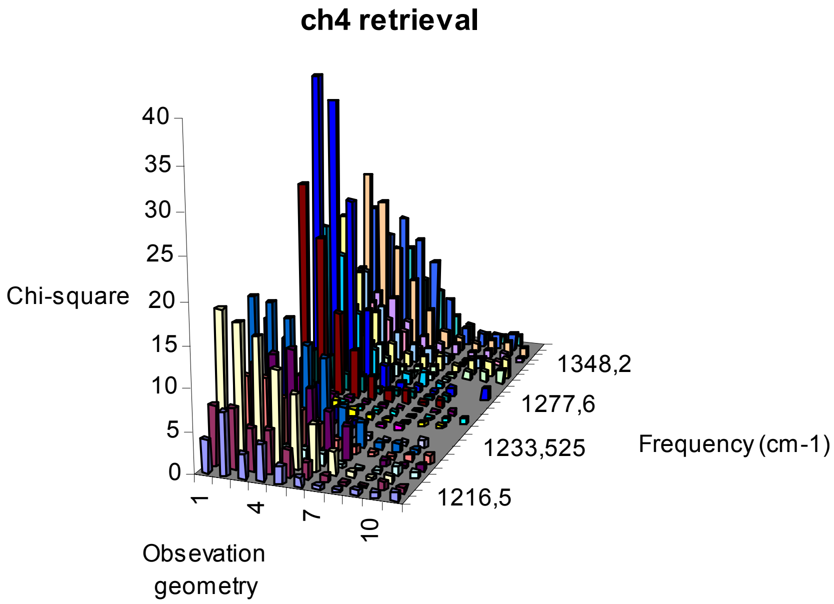


Figure 23 Results of CH4 VMR retrievals

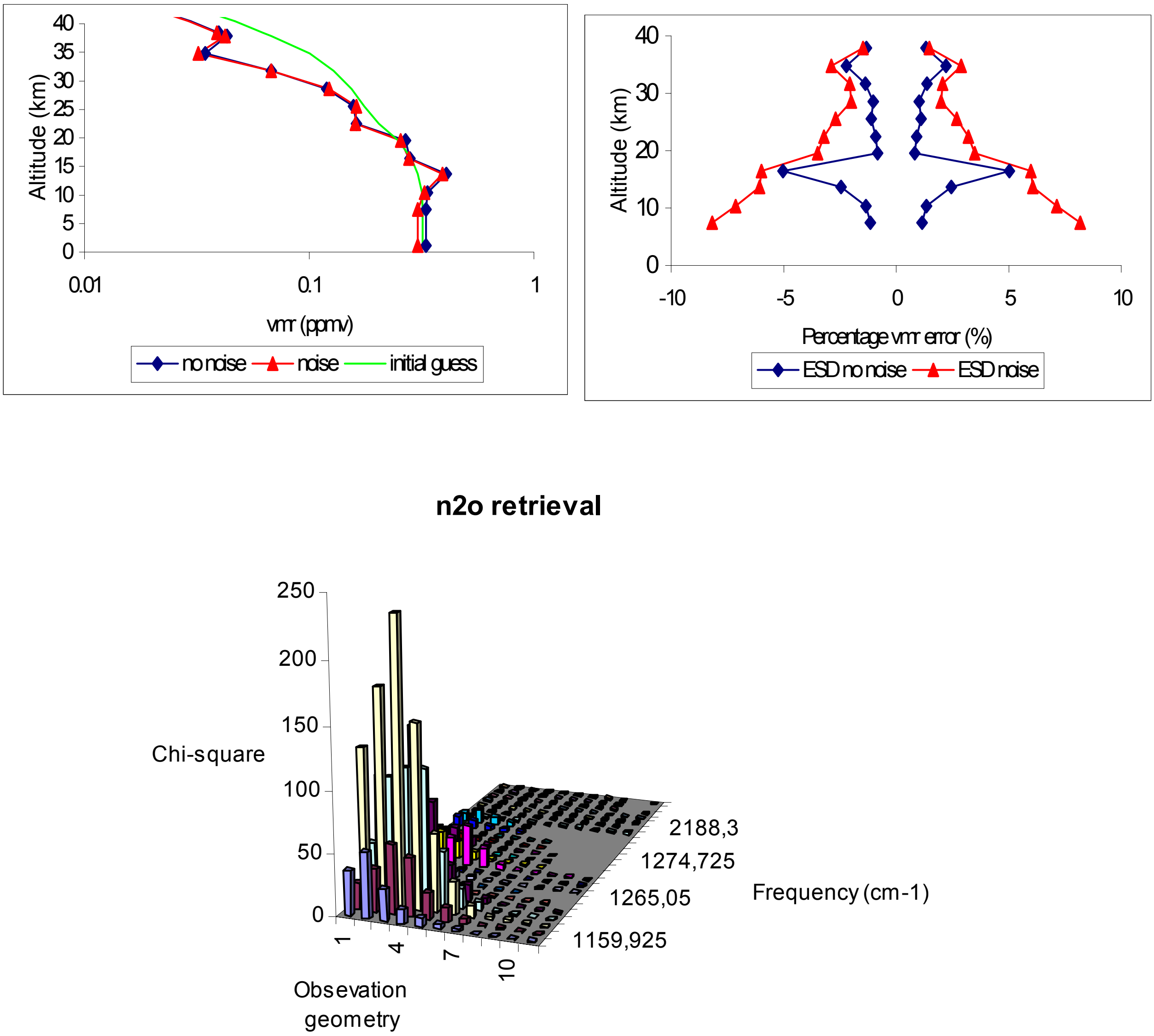


Figure 24 Results of N2O VMR retrievals

7. Conclusions

The exercise on real data has required a significant effort because of the numerous differences that exist between the satellite measurements and the balloon measurements, and because of the numerous effects that had to be taken into account in order to understand the observed inconsistencies. Nevertheless the exercise was necessary and provided a very important experience on many aspects:

- building competence on retrieval problems
- understanding the management difficulty of complex problems that depend on information diluted among many persons
- validating the ORM code

The latter was the main objective of the exercise and is not yet fully met, because an unique answer has not yet been found to the problem of altitude inconsistency between the retrieval and the engineering data. The following useful lessons have, however, been learnt:

- the criticality of automated occupation matrix. The occupation matrix that was built with an automated algorithm was considered to be unreliable during a critical analysis of the procedure and modifications were introduced by hand. This does not mean that the automated algorithm does not work, but that experimentalists do not yet trust it.
- tuning parameters have been used up to now as quantities left to the discretion of individual operators: a record should be kept of the tuning parameters that are used in each test.
- spectroscopic errors have been identified as a significant source of error especially if MIPAS radiometric performances turn out to be better than the original requirements
- the retrieval depends very much on the shape of the AILS.

The extension of the test exercise to other data sets, possibly obtained from space so that a wider set of altitudes and atmospheres is analysed, would probably be important before the commissioning phase.