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Results obtained during recent flights of the LPMAA balloon experiment and contribution to the ENVISAT validation

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Abstract

The LPMAA balloon experiment, based on a Fourier transform infrared (FTIR) spectrometer, has already proved its capabilities to prepare and to validate satellite missions : IASI mission, validations of ILAS and ODIN, second Atmospheric Chemistry Validation of ENVISAT (ACVE-2) ...

Several flights from August 2002 to March 2004 (LPMA19, LPMA20, IASI02, LPMA22) have been dedicated to the validation of ENVISAT instruments. Results from these recent flights are presented here. This contribution to the ENVISAT validation (MIPAS, SCIAMACHY) provides high vertical resolution profiles of trace species (CH_4 , N_2O , HCl , NO_2 , NO , CO , O_3 , HNO_3) from the upper troposphere to the lower stratosphere.

1 - Introduction

1.a - Description of the balloon-borne FTIR of the LPMAA

The Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique (LPMAA) has developed two infrared remote sensing instruments based on the same Fourier transform interferometer, a Bomem DA2.01 providing a maximum optical path difference of 50 cm. Each instrument, mounted into a stratospheric gondola with a pointing system [ref.1], is operated under large balloons (150000 m³ or 400000 m³) by CNES (Centre National d'Études Spatiales) to reach a height between 30 and 40 km. Depending on the scientific objectives, one instrument will be chosen in place of the another, allowing to study the concentration of the atmospheric trace gases located in the troposphere or in the stratosphere. For the cases discussed in this paper, flights in both configurations were dedicated to the validation of the ENVISAT satellite, launched in a sun synchronous orbit on

February 28th 2002, specially MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) and SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartography).

In its first configuration called Limb Profile Monitor of the Atmosphere (LPMA), the instrument operates in solar occultation [ref.2] and allows sounding of air masses from the upper troposphere to the middle stratosphere (tangent heights between 13 to 35 km). Figure 1 shows a schematics of the LPMA instrument and its gondola. The solar beam, after absorption by atmospheric constituents, is collected using a sun-tracker and is directed to the input of the interferometer. The LPMA spectrometer can observe numerous atmospheric trace gases at the same time in a large spectral range due to its dual channel output optics.

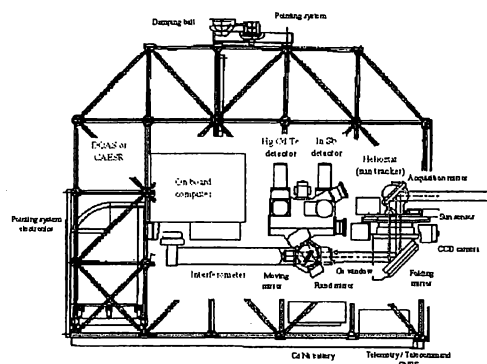


Fig.1 Schematic of the LPMA instrument and its gondola.

Three different optical configurations can be used depending of the targeted spectral regions, cf. Table 1. The long wave infrared (LWIR) configuration covers the spectral range from 650 cm⁻¹ to 4150 cm⁻¹ and is mainly used for MIPAS validation (same optical range as MIPAS), especially for trace gases like O_3 , HNO_3 , N_2O , CH_4 ,

NO₂, ... The short wave infrared (SWIR) configuration, from 2050 cm⁻¹ to 5320 cm⁻¹, is suitable for SCIAMACHY validation (covering the infrared channels or band 7 and band 8 of SCIAMACHY), especially for tropospheric N₂O, CO, CH₄, ... In the near infrared (NIR) configuration, the instrument covers the spectral region from 10300 cm⁻¹ to 13400 cm⁻¹ and has been used to validate GOMOS products in the O₂ A

band. Other scientific instruments can be accommodated in the same gondola : the DOAS (Differential Optical Absorption Spectroscopy) spectrometer from the Institut für Umweltphysik, University of Heidelberg, Germany or the Cold Atmospheric Emission Spectral Radiometer (CAESR) from Denver University.

Configuration	Detectors	Beamsplitter	Spectral range (cm ⁻¹)
LPMA(LWIR)	HgCdTe / InSb	KCl	650-1300 & 1750-2000 2750-3150 & 4100-4150
LPMA(SWIR)	InSb / InSb	CaF ₂	2050-2220 & 4220-4440 2700-3150 & 4770-5320
LPMA(NIR)	Si / Si	Quartz	10300-11000 12700-13400
IASI-Balloon	HgCdTe / InSb	KCl	650-2000 1800-3000

Table 1 : Different optical configurations of the balloon-borne instruments.

In the second configuration shown in Fig.2, the instrument named IASI-balloon (Infrared Atmospheric Sounding Interferometer), measures in the nadir viewing geometry, the thermal atmospheric emission of the surface/atmosphere system [ref.3]. This upwelling radiation is composed by several contributions as the emission of the Earth surface, the emission and absorption of atmospheric constituents, the emission of the clouds or the backscattered solar radiation. This down-looking configuration allows sounding of the low layers of the atmosphere, from the lower background surface, which could be the ground, water, forest, ..., to the actual height of the instrument.

The temperature of the sounded atmospheric scene and the operational temperature of the instrument are approximately the same at about 300 K. Therefore we have to radiometrically calibrate the measured spectra. Two well-characterised blackbodies stabilized at two different temperatures are needed to perform this absolute calibration by using the equation (1), [ref.3, ref.4] :

$$S_{\text{scene}}^{\text{calib}} = \frac{\epsilon_{\text{WBB}} B_{\text{WBB}} (S_{\text{scene}}^{\text{meas}} - S_{\text{CBB}}^{\text{meas}}) - \epsilon_{\text{CBB}} B_{\text{CBB}} (S_{\text{scene}}^{\text{meas}} - S_{\text{WBB}}^{\text{meas}})}{S_{\text{WBB}}^{\text{meas}} - S_{\text{CBB}}^{\text{meas}}} \quad (1)$$

In this equation ϵ_{WBB} and ϵ_{CBB} are the emissivities of the warm and cold blackbodies and B_{WBB} and B_{CBB} are the theoretical Planck functions at the appropriate temperatures. The radiometrically calibrated spectra of the atmospheric scenes covers the spectral range from

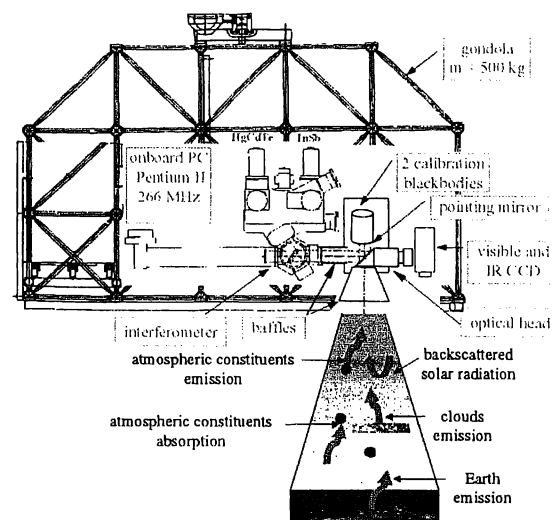


Fig.2 : Schematic of the IASI-balloon instrument and its gondola.

650 cm⁻¹ to 3000 cm⁻¹. IASI-balloon is used here to validate the total columns measured by SCIAMACHY in its nadir sounding mode. These two balloon-borne instruments LPMA and IASI-balloon, have been involved in several Announcement of Opportunities projects for validating the ENVISAT chemistry instruments.

Details for these dedicated flights are summarised in Table 2. The results retrieved (total columns or volume mixing ratio profiles) from several of these flights are presented in section 2 and 3. Some of these results have been already presented during the

ACVE-2 (Second Workshop on the Atmospheric Chemistry Validation of ENVISAT) workshop in May 2004 [ref.5] or will be published soon in scientific journals [ref.6].

Date	Flight	Location	Principal trace gases	Validation
05/08/2002	IASI02	Kiruna, Sweden	O ₃ ; CH ₄ ; N ₂ O; CO	SCIAMACHY
19/08/2002	LPMA18 (NIR)	Kiruna, Sweden	H ₂ O; O ₂ A band	GOMOS
04/03/2003	LPMA19 (LWIR)	Kiruna, Sweden	HNO ₃ , N ₂ O, NO ₂	MIPAS
23/03/2003	LPMA20 (SWIR)	Kiruna, Sweden	CH ₄ , CO, N ₂ O, NO ₂	SCIAMACHY
09/10/2004	LPMA21 (SWIR)	Aire-sur-l'Adour, France	CH ₄ , CO, N ₂ O, NO ₂	SCIAMACHY
24/03/2004	LPMA22 (LWIR)	Kiruna, Sweden	HNO ₃ , N ₂ O	MIPAS

Table 2 : Balloon flights performed during ESABC validation campaigns.

1.b - The retrieval algorithm LARA

In order to retrieve the concentration of the atmospheric trace gases from their spectral signatures observed in our spectra, we have to

model the infrared radiance at the entrance of the interferometer. This radiance can be represented by the radiative transfer equation :

$$L_{\bar{\nu}}(M) = L_{\bar{\nu}}(M_0) T_{\bar{\nu}}(M_0, M) + \int_{M_0}^M J_{\bar{\nu}}(s') T_{\bar{\nu}}(s', M) \alpha(s') ds' \quad (2)$$

where $L_{\bar{\nu}}(M)$ is the radiance observed at point M (along the line of sight) by the instrument in unit of $W/(cm^2 sr cm^{-1})$, $L_{\bar{\nu}}(M_0)$ is the radiance of the background (at the lower boundary M_0 of the line of sight), $T_{\bar{\nu}}(M_0, M)$ is the atmospheric transmission along the line of sight between the points M_0 and M , $J_{\bar{\nu}}(s')$ is the source function at any point between M_0 and M , and $\alpha_{\bar{\nu}}(s')$ is the absorption coefficient. The first term gives the background emission after transmission in the atmosphere and the second term corresponds to thermal emission of different atmospheric layers along the line of sight. Table 3 gives more details about the LPMAA Atmospheric Retrieval Algorithm (LARA) [ref.7], especially the different input parameters used by LARA, as the spectroscopic data base (Hitran 2004 here), the water vapour continuum (CKD 2.4), ... The forward model is combining spectroscopic parameters (position, intensity and broadening coefficient of the absorption lines), geometric and instrument parameters (flight trajectory and profile, instrument line shape) and retrieval parameters (surface temperature, columns or vertical profiles), to calculate the theoretical spectrum. After the forward model, a minimization algorithm based on a Levensberg-Marquardt method, allows to fit this calculated spectrum to the measured one.

Forward Model :	Hitran 2004 CKD 2.4 (H ₂ O) water vapour continuum χ factor for CO ₂ , collision induced absorption for N ₂ and O ₂ Water vapour self-broadening Reflected downward flux Emission / Transmission Nadir or limb viewing User defined spectral spacing Effective temperature and pressure in layers (number density weighted) Line mixing for CO ₂ Convolution in the spectral domain Pre-calculated absorption cross-sections (look-up tables)
Minimisation algorithm :	Global fit approach Retrieved parameters Instrumental line shape Instrumental spectral shift Vertical VMR columns and/or profiles Surface temperature (nadir) Surface emissivity (nadir)

Table 3 : LPMAA Atmospheric Retrieval Algorithm (LARA).

2 - Validation of SCIAMACHY in nadir looking with IASI-balloon

2.a - The second flight of IASI-balloon

The IASI-balloon instrument has flown for its second flight from Kiruna (Sweden, 68° N, 21° E), the 5th August 2002 (between 18:30 UT and 22:10 UT with 2 hours and 30 min at float). This flight was dedicated to the validation of SCIAMACHY in its nadir sounding mode. The flight took place at the end of daytime with a night transition, in rather warm conditions (in Arctic summer). The background surface was either ground, lakes or rivers, forests, mountain areas, ... In order to characterise the atmospheric scene observed by IASI-balloon, a visible CCD and an infrared camera were used. These two imagers are co-aligned with the spectrometer's instantaneous field of view, which is represented by a circle in the infrared pictures of Fig.3. The dark colours, cf. Fig.3a, correspond to cold pixels like clouds, which are at higher altitude and colder than the ground. Ground surface, rivers or lakes are warmer than the clouds and appear in clearer colours, cf. Fig.3b.

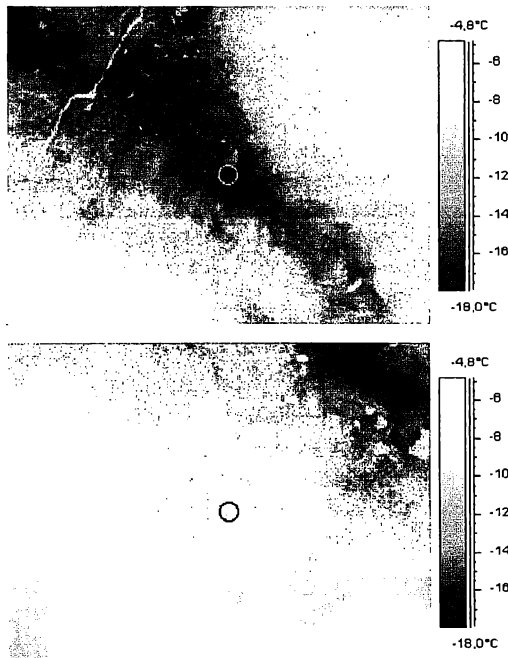


Fig.3 : Night-time infrared pictures recorded during the flight IASI02 (top (Fig.3a) - bottom (Fig.3b)).

Figure 4 shows two radiometrically calibrated spectra of the atmosphere recorded at float around 31 km, for a clear sky case. The brightness

temperature of the background surface is around 265.45 K. The good superposition of these two spectra in the overlap region between 1850 and 1920 cm^{-1} , confirms the good performances of the IASI-balloon instrument. Several absorption bands of CO_2 , O_3 , N_2O , CH_4 , H_2O and CO can be observed.

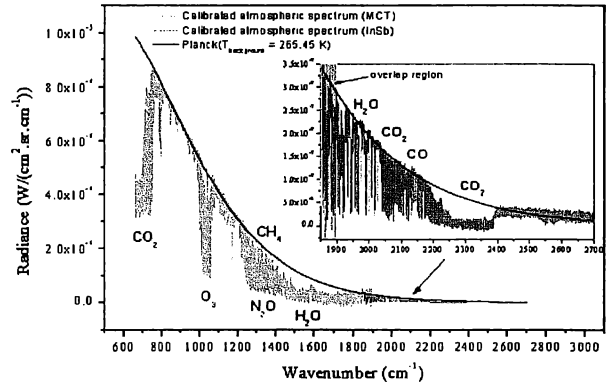


Fig.4 : Radiometrically calibrated atmospheric spectra recorded by IASI-balloon.

2.b - Comparison between IASI02 and SCIAMACHY in nadir sounding

The total columns of CH_4 and O_3 measured during the IASI02 flight are compared to those obtained by SCIAMACHY operating in the nadir looking in the same day. Figure 5 shows the good co-location (latitude and longitude) between the IASI-balloon and SCIAMACHY footprints (less than 600 km). On Fig.5, the mean value of the total columns of CH_4 measured by IASI-balloon is represented in red and is compared to the corresponding columns obtained by SCIAMACHY from band 7 (cf. Fig.5a) and from band 8 (cf. Fig.5b). SCIAMACHY band 7 underestimates the balloon CH_4 total columns by about 25%. And the CH_4 columns derived from SCIAMACHY band 8 show strong and strange variations.

The comparison between the balloon and satellite O_3 columns is shown in Fig.6. Ozone results derived from SCIAMACHY band 1, show a positive bias of about 30% compared to the balloon ones as seen in Fig.6a. Some ozone column results from band 2 are negative as seen in the colour-coded map of Fig.6b. The official products of ESA for our balloon flight have not been reprocessed because of instrument problems with SCIAMACHY in that period.

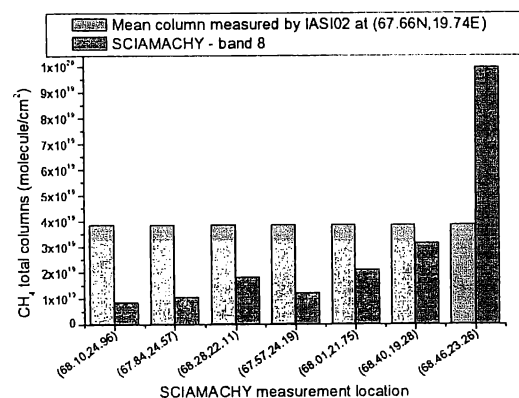
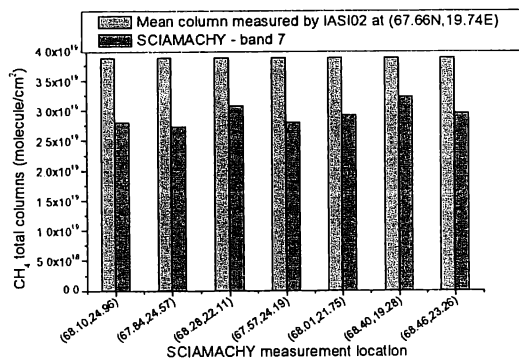


Fig.5 : Total columns of CH₄ measured by IASI-balloon and SCIAMACHY (top (Fig.5a) - bottom (Fig.5b)).

3 - Validation of SCIAMACHY and MIPAS with LPMA

3.a - The LPMA19 and LPMA22 flights

The LPMA19 and LPMA22 flights were performed from Esrange (Kiruna, Sweden) with take-off at 13:20 UT on March 4th 2003 and at 14:05 UT on March 23rd 2004 respectively. The long wave infrared (LWIR) optical configuration was used for both flights. Fig.7 shows an example of spectra recorded during the LPMA19 flight. A dichroic is used to split the spectral range of the spectrometer. Then for each infrared channel, this spectral range is split again using optical and numerical filters in order to optimise the signal to noise ratio and the data rate. Absorption bands of several atmospheric trace gases like CO₂, O₃, N₂O, NO₂, HCl, CH₄, H₂O, HF, HNO₃, can be observed in the four windows.

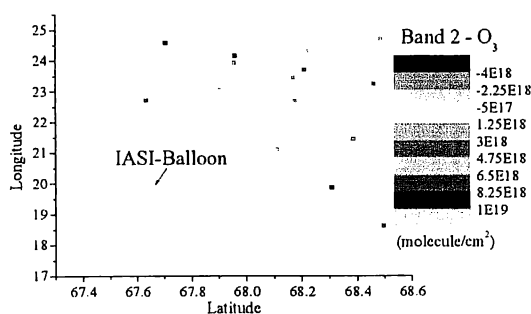
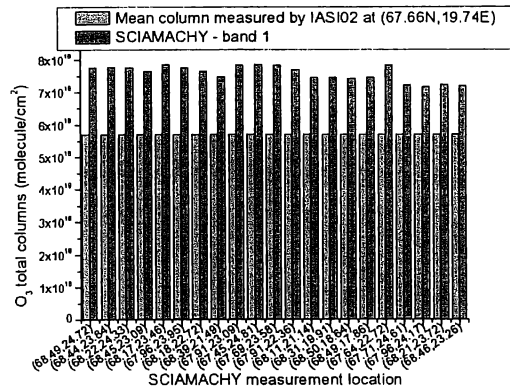


Fig.6 : Total columns of O₃ measured by IASI-balloon and SCIAMACHY (top (Fig.6a) - bottom (Fig.6b)).

3.b - Comparison between MIPAS and LPMA19

The satellite profiles considered here have been measured during the same day as the LPMA19 flight. The mean position is 65.7°N and 13.4°E at 21:13 UT. During sunset, data have been recorded by the LPMA instrument for locations of the tangent points between (66.7°N and 22.8°E) and (66.1°N and 15.6°E). The spatial and temporal collocation is then quite good. Figure 8 presents the comparison between balloon and satellite results for O₃. The profile (in red) obtained by version v4.61 of the ESA operational retrieval algorithm shows strong oscillations. But the IMK scientific profile is smoother with a difference less than 8% as compared to the LPMA sunset profile. The IMK profile is representative of the expected MIPAS results when a final version of the operational retrieval algorithm is available.

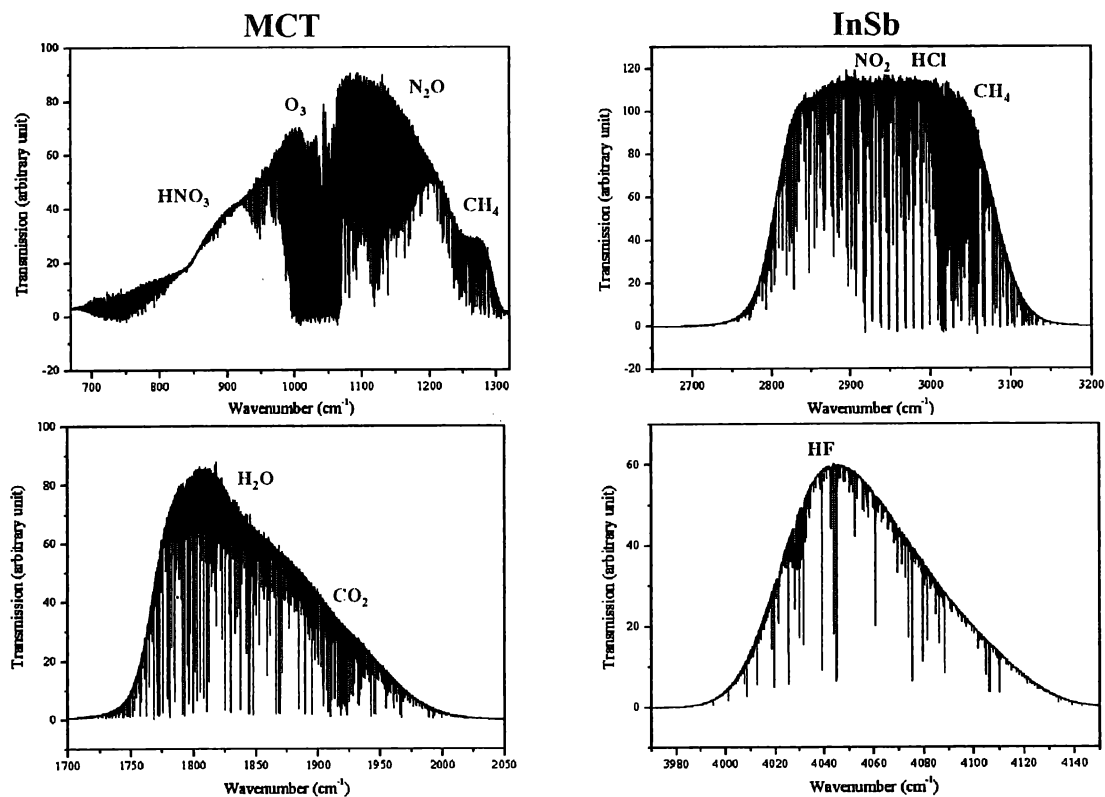


Fig.7 : Spectra recorded by the LPMA instrument during the LPMA19 flight.

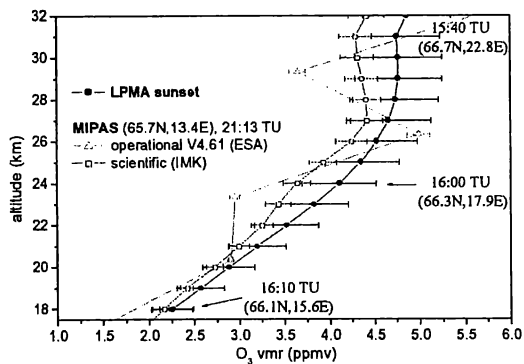


Fig.8 : O₃ profile measured by LPMA19 and MIPAS.

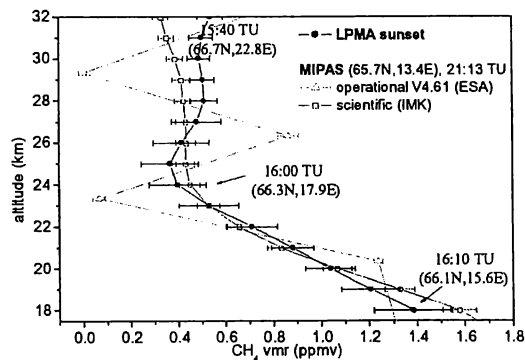


Fig.9 : CH₄ profile measured by LPMA19 and MIPAS.

In the comparison of CH₄ profiles, strong oscillations can be also observed in the ESA operational profile, cf. Fig.9. The IMK scientific profile of CH₄ agrees very well with the LPMA profile, within the error bars.

The last comparison concerns the N₂O molecule. Figure 10 shows a good agreement between the three profiles (scientific, operational and balloon). But this agreement is a little worse than for CH₄, with maximum differences of about 30%.

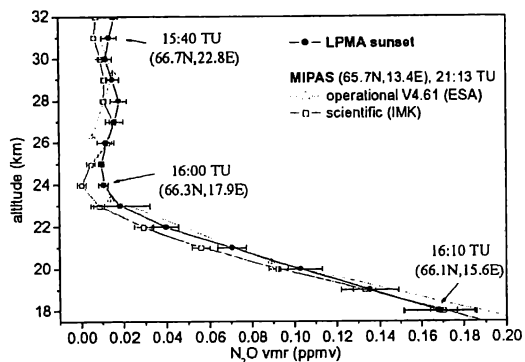


Fig.10 : N₂O profile measured by LPMA19 and MIPAS.

The last version of the ESA operational algorithm of MIPAS is v4.62. Data recorded by MIPAS for LPMA19, have not yet reprocessed. But generally, the reprocessed operational profiles have been improved (no or smaller oscillations).

3.c - Comparison between LPMA and SCIAMACHY in limb sounding

The flights LPMA19 and LPM22 were originally dedicated to the validation of MIPAS products, but some results can be used also for the validation of the SCIAMACHY instrument in limb sounding (the same sounding geometry as for the LPMA instrument). Results derived from the LPMA19 flight were provided by the French LPMA instrument team. Preliminary results from the LPMA22 flight were produced by the German DOAS instrument team. For the validation of O₃, Fig.11 shows (in grey diamond) the LPMA sunset profile of O₃ with its high vertical resolution, (in blue open diamond) the same profile degraded to the SCIAMACHY vertical resolution (lower) and (in red circle) the SCIAMACHY profile itself. The concentrations inferred from the satellite instrument agree with the balloon-borne results in the available altitude range from 18 km to 32 km with a maximum difference of about 20%. A slightly negative altitude offset in the satellite profile is observed.

For Fig.12, the same representation is used with the square symbol for the balloon-borne ascent profiles and the green dashed line for the O₃ sonde from Esrange. The comparison between satellite and balloon results reveals a good agreement within the

error bars, in the altitude range from 22 km to 32 km. The relative differences are smaller than 20%. But below 22 km, the agreement is poor and the difference is larger than 50%, although the coincidence of the measured air masses is quite good between 10 km and 20 km.

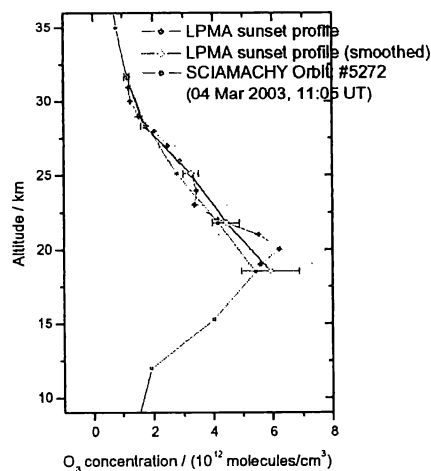


Fig.11 : O₃ profile measured by LPMA19 and SCIAMACHY.

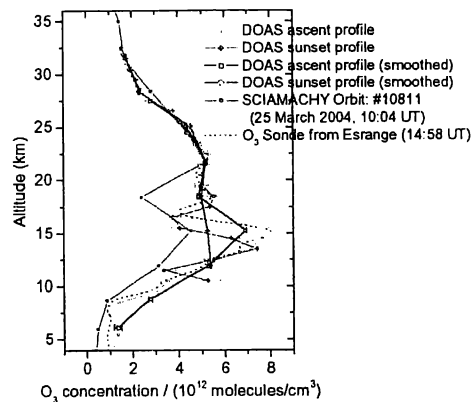


Fig.12 : O₃ profile measured by LPMA22 and SCIAMACHY.

The NO₂ validation study is represented in Fig.13. Since the NO₂ molecule shows strong photochemical variations (between day and night time), a photochemical correction model is needed. The same symbols and colours as in previous figures are used. The only difference is that the blue open diamond represents the balloon profile convolved to the SCIAMACHY vertical resolution

but with the photochemical correction. The comparison is performed for the same air masses measured by the SCIAMACHY instrument before and after the balloon flight. For both cases, a quite good agreement between satellite and balloon results is observed (within the combined errors bars). The maximum differences are at most 30% between 18 km and 32 km.

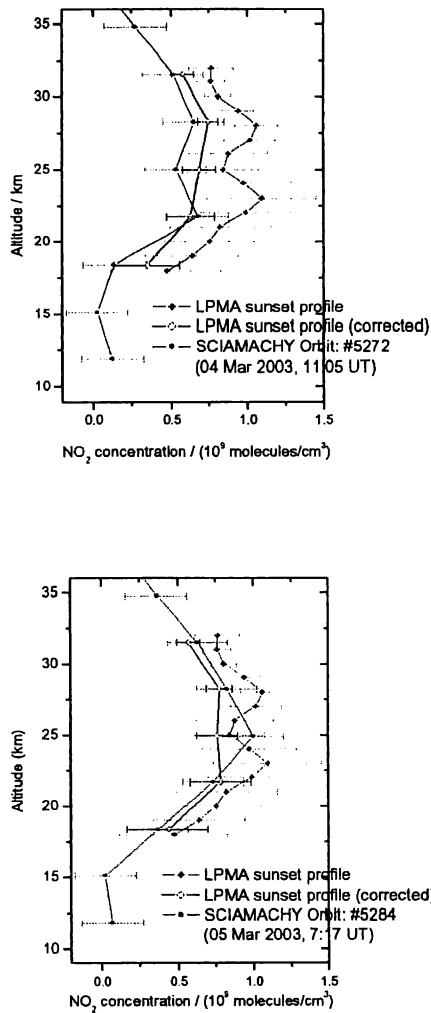


Fig.13 : NO₂ profile measured by LPMA19 and SCIAMACHY (before the balloon flight (top) - after the balloon flight (bottom)).

The comparison between SCIAMACHY and LPMA22 results is shown in Fig.14. The square symbol represents again the balloon ascent measurements. The satellite results agree very well with the balloon ones in the altitude range from

12 km to 32 km. The differences are smaller for the "satellite before balloon" case (top figure). The differences are a slightly larger for the "satellite after balloon" case (bottom figure).

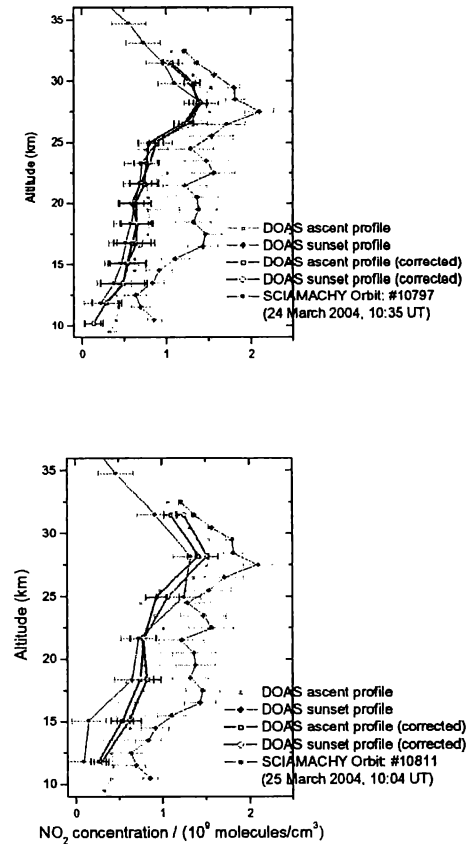


Fig.14 : NO₂ profile measured by LPMA22 and by SCIAMACHY before the balloon flight (top) or after the balloon flight (bottom).

4 - Conclusion

This paper has discussed the results obtained with the two versions of the LPMAA experiment that have been used for the validation of the ENVISAT instruments MIPAS and SCIAMACHY. The agreement between satellite and balloon results are encouraging. As a rough conclusion, the SCIAMACHY data for August 5th 2002 provided in the officially distributed ESA products are not reliable, because of possible calibration problem for that period. The operational algorithm of MIPAS, shows, for version v4.61 strong oscillations, which have more or less been suppressed in version v4.62.

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