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THE LPMA BALLOON-BORNE FTIR SPECTROMETER FOR REMOTE SENSING OF ATMOSPHERIC CONSTITUENTS

C. Camy-Peyret (1), **P. Jeseck** (1), **T. Hawat** (2), **G. Durry** (1), **S. Payan** (1), **G. Berubé** (3), **L. Rochette** (3) and **D. Huguenin** (4)

(1) *Laboratoire de Physique Moléculaire et Applications, CNRS/UPMC, Case 76, 4 place Jussieu, 75252 Paris Cedex 05, France*

(2) *Institut d'Électronique et de Micro-Électronique du Nord, Dépt. OAE, UVHC, Bte 311, 59304 Valenciennes, France*

(3) *BOMEM inc., 450 Av. St-Jean-Baptiste, Québec, Québec G2E 5S5, Canada*

(4) *Observatoire de Genève, CH-1290 Sauverny, Suisse*

ABSTRACT

A stratospheric gondola with azimuth stabilization is used to operate a new Fourier transform infrared spectrometer for high resolution absorption spectroscopy measurements of atmospheric trace species using the sun as a source. The characteristics of the pointing system are detailed and the Limb Profile Monitor of the Atmosphere (LPMA) instrument with its specially designed two detectors output optics and its on-board processing system are described. Examples of performances achieved during flights from Aire-sur-l'Adour in France and ESRANGE in Sweden during the SESAME campaign are given, particularly for the chlorine family (HCl and $ClONO_2$).

Keywords: Stratospheric balloon, Azimuth control, Fourier transform infrared spectroscopy, Solar occultation, Chlorine species.

1. INTRODUCTION

The Limb Profile Monitor or the Atmosphere (LPMA) is a Fourier transform infrared (FTIR) spectrometer designed to retrieve stratospheric (and in some cases tropospheric) trace species concentration profiles from atmospheric spectra recorded in absorption using the sun as a source. It can operate under stratospheric balloons on a gondola with pointing capabilities. With proper azimuth stabilization, an heliostat can be used to feed the solar radiation into the LPMA instrument. This Michelson type interferometer with an apodized resolution of $0.020\ cm^{-1}$ is equipped with a two channels output optics and is capable to sample simultaneously the interferograms produced by two infrared detectors: one HgCdTe for covering the 10 μm region and one InSb for the 3 μm region. The sampled interferograms are numerically filtered and are both stored on board and sent to the ground through high data rate telemetry. After flight the interferograms are processed to produce high resolution atmospheric spectra from which vertical concentration profiles of trace species can be retrieved.

In the present paper we will describe in succession the gondola and its pointing capabilities, the FTIR instrument with its two detectors output optics and the on-board processing system. Finally we will present some of the results obtained during two successful flights of the instrument respectively at mid-latitude in the fall from Aire-sur-l'Adour and at Artic latitude in winter from ESRANGE.

2. THE GONDOLA AND ITS POINTING SYSTEM

The gondola used to accomodate the FTIR instrument described here results from the established expertise of Geneva Observatory in the operation of stratospheric payloads (Ref. 1) for astrophysical studies and from experience with an analogous gondola used for atmospheric studies (Ref. 2).

For atmospheric spectroscopy in absorption using the sun as a source it is necessary to have the capability to stabilize the gondola in azimuth in the proper direction. This is not a trivial problem particularly for a rather large payload (Fig. 1), but this is still more difficult if proper pointing is to be maintained during ascent *i.e.* in the dense layers of the atmosphere. The azimuth suspension shaft of the present gondola is mounted on a thrust ball-bearing and driven by a DC servo-motor and gear-box. A torque limiter prevents overtwisting of the flight chain and parachutes. The motorized azimuth swivel is coupled to the upper beam of the gondola by a torquemeter and a universal joint. The signal from the torquemeter is fed to a regulator which produces a fast and linear response of the swivel over more than two decades of torque and reduces the dry friction of the azimuth thrust bearing by a factor 50. The general characterisitics of the pointing system are given in Table 1. The pointing stability during ascent depends very much upon the quality of the azimuth position and rate sensors. With a good gyrocompass reference, the stability is around 1 degree in the troposphere, except during occasional wind gusts, 0.5 to 0.1 degrees in the lower stratosphere, and 1' or better at a float altitude of 33 km or higher. These performances are degraded by a factor 3 when the azimuth reference is a magnetometer, due to a strong coupling between axes inherent to this type of device. This is the situation with the present LPMA gondola but an heliostat described in Ref. 3 has the additional tracking capabilities to accept the corresponding azimuth and elevation fluctuations.

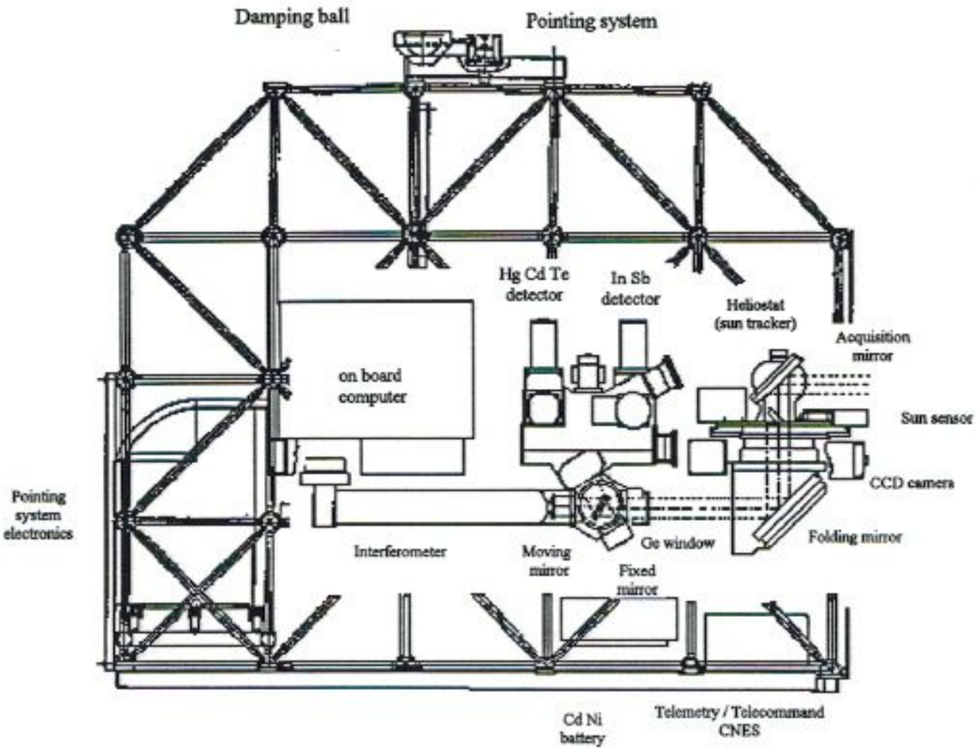

Figure 1: Schematics of the LPMA gondola. The overall size is 2 m × 1.6 m × 1.4 m and the mass is 530 kg (including the Denver University CAESR instrument not represented here)

2 versions:	500 kg or 3000 kg gondolas
2 interfaces with azimuth sensor:	analog and digital
high peak torque:	1 to 4 N.m, adjustable
very low residual friction:	0.02 N.m (for 3000 kg)
high stability:	0.25' to 1.54' at float
very low power:	28 V/9 W average
low mechanical noise:	no activated bearing, helicoidal gears
mechanical strength:	10 g, NASA/NSBF specifications
environment:	cold start - 65°C, operation - 85°C condensing water, snow, dust proof

Table 1: Characteristics of the azimuth swivel (or pivot) developed at Observatoire de Genève for the primary stabilization of stratospheric gondolas.

To reduce the inter-axes coupling a pendulous oil damper attenuates the pitch and roll oscillations of the gondola with a time-constant of about 20 to 30 s. Finally, a momentum cross is mounted on the suspension cable, 2 m above the gondola. Its inertia is used to improve the time response of the swivel and a friction coupling with the cable damps the torsion oscillations of the flight chain.

3. THE NEW LPMA INSTRUMENT

The instrument used in this balloon borne atmospheric application is a Michelson interferometer with plane mirrors of the BOMEM DA2.01 type, *i.e.* having an effective aperture of 45 mm and producing a maximum path difference of $\Delta_{\max} = 50\,\mathrm{cm}$, leading to an apodized resolution of $1/\Delta_{\max} = 0.020\,\mathrm{cm}^{-1}$.

The standard BOMEM instrument has been upgraded in two aspects: a two channels output optics and a dedicated on-board processing system.

The general characteristics of the new LPMA instrument are given in Table 2.

Fourier transform spectrometer:	BOMEM DA2.01
maximum moving mirror displacement:	25 cm
maximum optical path difference:	$\Delta_{max} = 50$ cm
apodized resolution:	$\delta\tilde{\nu} = 1 / \Delta_{max} = 0.020\ \mathrm{cm}^{-1}$
2 detectors output optics	
HgCdTe:	$D^{*} = 4.0 \times 10^{10} \mathrm{cm\,Hz}^{1/2} / \mathrm{W}$
InSb:	$D^{*} = 1.2 \times 10^{11} \mathrm{cm\,Hz}^{1/2} / \mathrm{W}$
on-board processing:	PC Pentium
choice of 2 numerical filters per channel	
on-board recording:	magneto-optical disk
high data rate TM:	500 kbits/s
housekeeping TM and TC:	9600 bits/s
new 1.5 GHz CNES TM/TC	

Table 2: General characteristics of the new LPMA instrument.

3.1 The two detectors output optics

Because of the limited number of flight opportunities for large payloads, it is important to maximize the amount of geophysical information acquired during one single flight. Measurements during both ascent and sunset at float are one step into this direction. The capability to cover 2 spectral regions with a 2 detectors output optics (Fig. 2) is another way to increase the scientific return of one given flight. This is particularly true for example, if simultaneous measurements of the major chlorine reservoir species are to be achieved (*i.e.* $ClONO_2$ at 12.8 µm and HCl at 3.4 µm since it is not possible to reach high responsivity in these two widely different spectral regions with only one infrared detector).

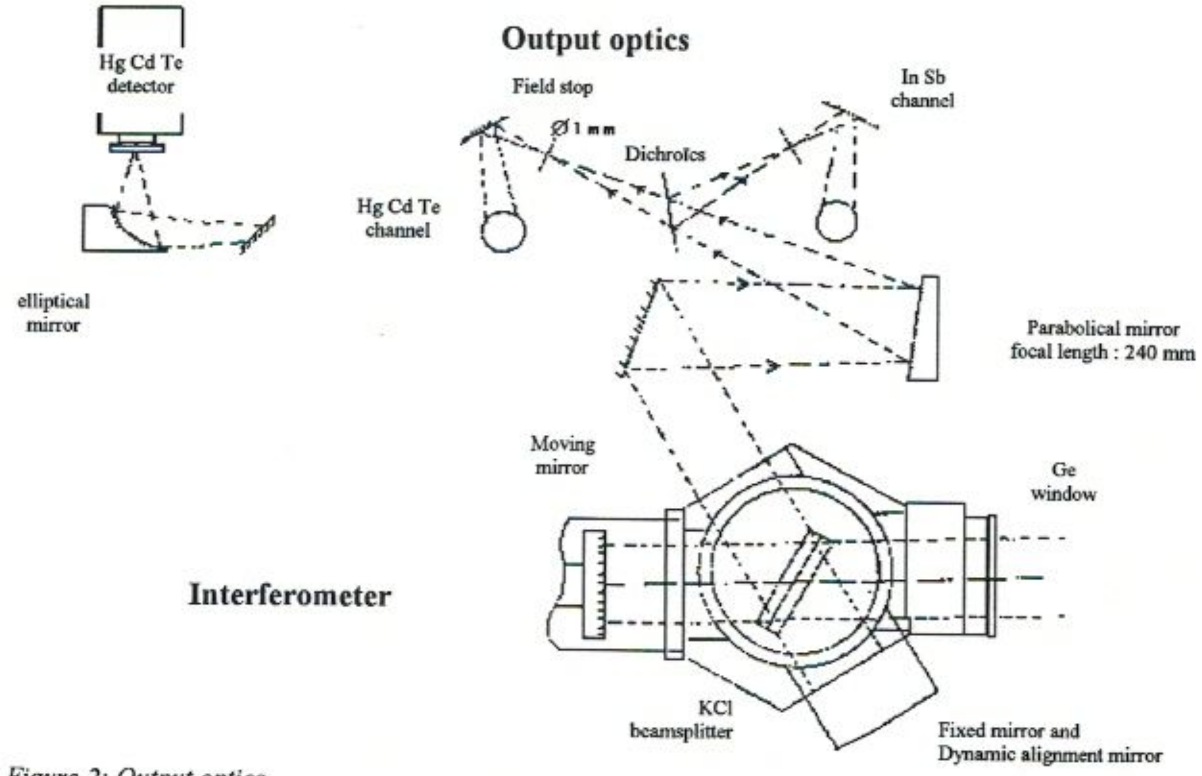

Figure 2: Output optics

So at the output of the KCl beamsplitter, the infrared radiation is separated (Fig. 2) by a dichroïcs into a long wavelength region (transmission) and a shorter wavelength region (reflection). These two optical beams are respectively focused on the HgCdTe and the InSb detector both cooled to liquid nitrogen.

3.2 Numerical filtering

After proper preamplification, the output signals of the two detectors are sampled during each scan at the fringe frequency of a stabilized He-Ne laser also used for dynamic alignment. For a scanning speed of the moving mirror of 0.5 cm/s the sampling frequency is 15.8 kHz and each incoming interferogram is converted with 2 ADCs with gains differing by a factor of 8 to match the large dynamic range of the signals between zero and maximum path difference. For one scan (forward or reverse) of 50 s duration each, the number of points is about 800 000 per channel and direct recording or transmission would be impractical. To circumvent this problem the data processing unit (based on a Pentium microprocessor) is performing real time numerical filtering of each interferogram to extract (at most) two spectral windows per channel by an appropriate choice of the convoluting filters. This allows firstly a large reduction (by about a factor 10) of the data rate for on-board recording on a magneto-optical disk or telemetry transmission and secondly an optimization of the signal to noise ratio by combining numerical filtering with appropriate optical filters isolating the spectral bands of interest. The schematics of the data processing is shown in Fig. 3. To optimize data storage and transmission 4 vectors are produced for each channel: the unfiltered interferograms at high and low gain around zero path difference (ZPD), and the two high gain filtered interferograms (A & B) from ZPD (slightly before it in fact) up to maximum path difference (MPD). All these data together with the corresponding data for the other channel are combined in a single file (~ 400 kbytes) which is transmitted to the ground through a high data rate link (RS 422 at 500 kbit/s) and recorded on-board (this added redundancy is valuable in case of TM drop-outs).

The reconstruction of a consistent interferogram from ZPD to MPD is performed after flight using the composite file described above. The unfiltered interferograms around ZPD are used to determine the phase correction to be applied to recenter the filtered interferograms and to regenerate, after fine adjustement of the interferogram values in their common region, the proper filtered values in the ZPD region (not available with the high gain filtered interferogram because of the × 8 gain producing out of scale values in that region). The final data (a maximum of 4 recentered interferograms per scan) can then be Fourier transformed and the corresponding spectra displayed for further inspection and analysis on the ground processing station (based on a PC 486) which is also used as a TM/TC station during the flight. In that latter case the display is used to visualize in real time various housekeeping signals from the instrument (peak ZPD signals, internal temperatures, laser parameters, alignment status...) transmitted to the ground station through a RS 232 TM downlink at 9600 bit/s. The same PC can be used simultaneously to uplink various operational parameters (mainly the commandable preamplifier gain of each channel) to optimize the observed peak amplitudes to the proper ADC range when the air mass is changing (which is often necessary when performing solar absorption measurements). This TC uplink (RS 232 at 9600 bit/s) is also used to setup the various recording parameters (resolution, numerical filters, ...).

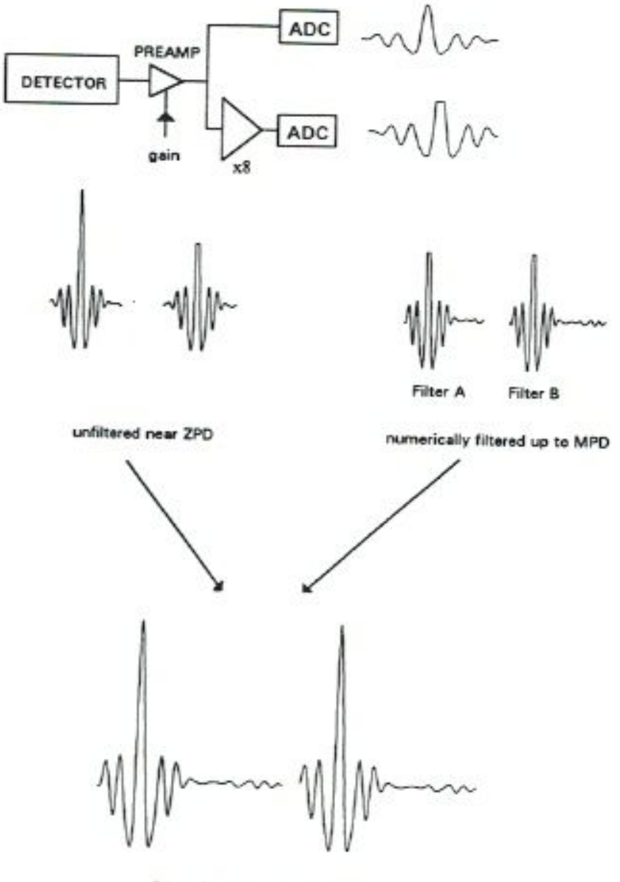

Figure 3: On-board processing

4. THE 28 OCTOBER FLIGHT (LPMA01) FROM AIRE-SUR-L'ADOUR

The first flight of the LPMA gondola and instrument was performed successfully from Aire-sur-l'Adour (43.7 N) on 28 october 1994 during phase 2 of SESAME (Second European Stratospheric Arctic and Mid-latitude Experiment).

The corresponding flight profile (Fig. 4) shows that continuous recording of atmospheric spectra was performed from an altitude of about 12 km (scan # 54) up to float (scan # 143) and finally until flight termination (scan # 210 with the sun still acquired at an elevation of - 3.9° *i.e.* a tangent of 19 km;

recovery constraints prevented waiting till complete loss of sun). Fig. 5a and 5b represent the overall spectral domain covered with the HgCdTe detector for a high sun and a low sun scan whereas corresponding spectra for the InSb detector (only one numerical filter per channel was used) appear in Fig. 6a and 6b. A zoom in the 3.4 µm region is shown in Fig.7 with a typical micro-window used for the HCl retrieval. The calculated spectrum results from a global fit of about 140 microwindows (involving 3 intervals per scan and covering the HCl lines around 2926, 2945 and 2963 cm^{-1}). The corresponding preliminary mixing ratio profile of HCl is shown in Fig. 8.

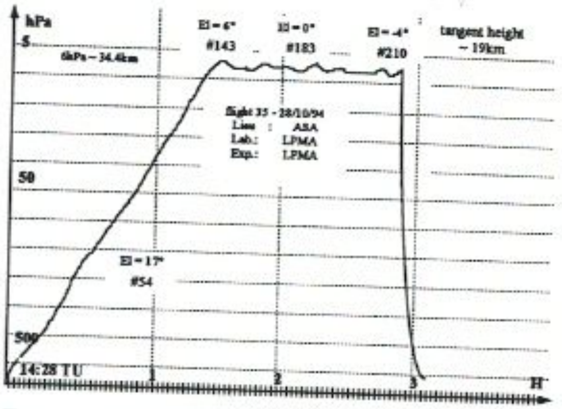

Figure 4: LPMA01 flight profile from Aire-sur-l'Adour.

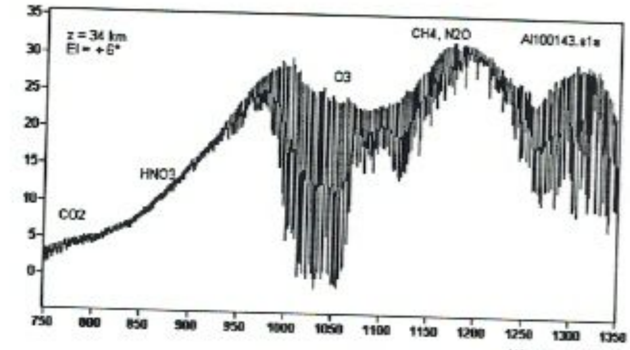

Figure 5a: Overall high sun spectrum in the HgCdTe region.

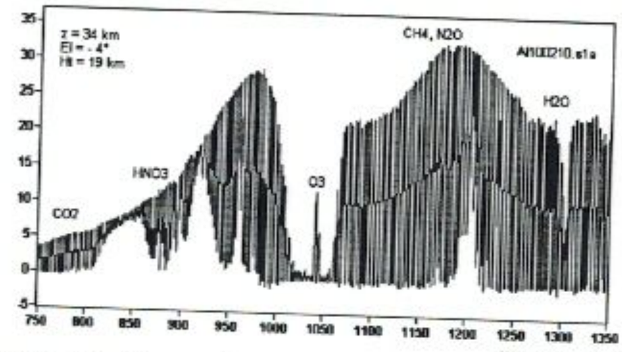

Figure 5b: Same as Fig. 5a for a low sun spectrum

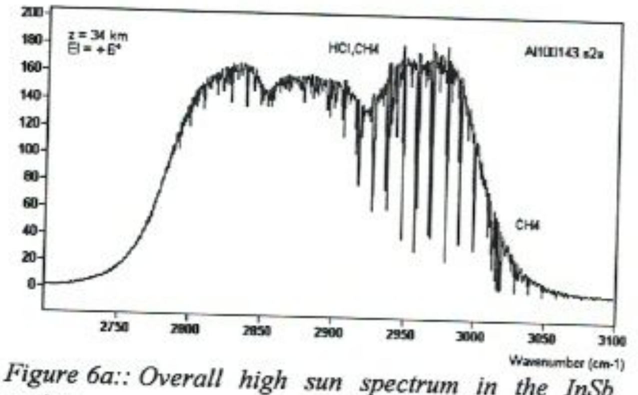

Figure 6a:: Overall high sun spectrum in the InSb region.

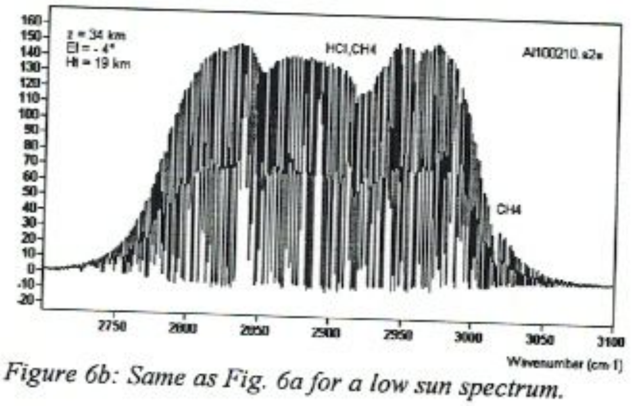

Figure 6b: Same as Fig. 6a for a low sun spectrum.

5. THE 22 MARCH FLIGHT (LPMA04) FROM ESRANGE

A second very successful flight was performed from ESRANGE (67.9 N) during phase 3 of SESAME inside the vortex on 22 march 1995. A very exceptional flight trajectory was possible with a rather long duration at float (more than 1 h 20 mn until loss of sun below a high cloud deck at 11 km altitude) with a corresponding very slow horizontal drift due to very light stratospheric winds (less than 5 m/s) at the center of the vortex and at the 9 hPa level reached for this flight. Very interesting simultaneous series of spectra of HCl and $ClONO_2$ have been obtained. The absorption at the center of the $ClONO_2$ Q branch at 780 cm^{-1} reaches about 50 % demonstrating a very large abundance of this species in the late polar vortex conditions. Many other interesting species could be retrieved from these high resolution spectra, particularly HNO_3 which will be compared with similar data obtained on the same gondola by the CAESR instrument of Denver University, using emission spectroradiometry and looking in the opposite direction from the sun.

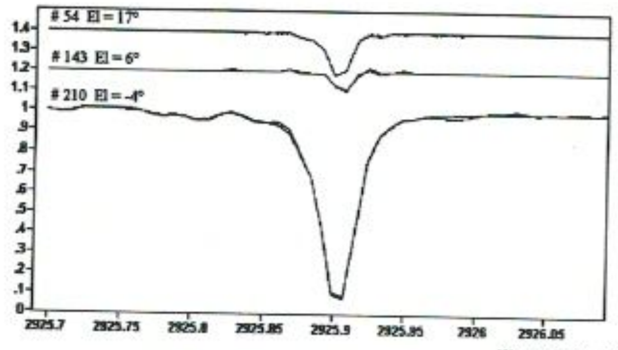

Figure 7: HCl micro-window around 2926 cm^{-1} for 3 representative viewing geometries (#54 during ascent, #143 at float and #210 at sunset)

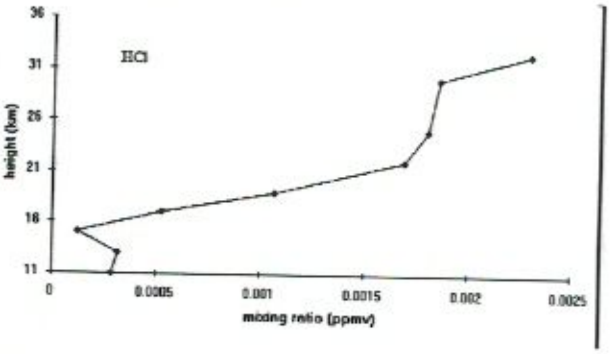

Figure 8: Mixing ratio profile of HCl retrieved for the LPMA01 flight from Aire-sur-l'Adour on 28 october 1994.

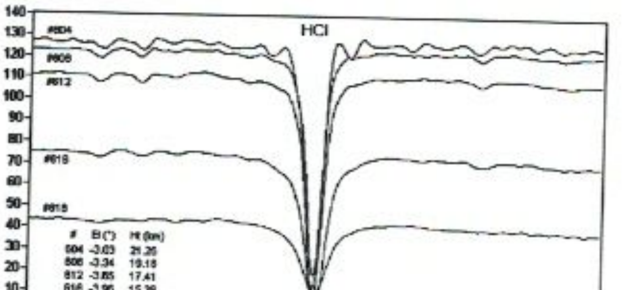

Figure 9: HCl spectra recorded during the LPMA04 flight from ESRANGE on 22 march 1995. Note the strong backgroung attenuation at the lower tangent altitudes (all spectra are plotted on the same scale).

6. CONCLUSION

The new LPMA instrument and ancillary equipment is now operational under a dedicated stratospheric gondola. The performances of the system are very encouraging for providing simultaneous profiles of several trace constituents related to the ozone layer chemistry particularly the chlorine (HCl and $ClONO_2$) and nitrogen (HNO_3) reservoirs. One great advantage of a two channel FTIR instrument is to cover rather large spectral intervals that include appropriate spectral signatures of many atmospheric species. In addition to HCl and $ClONO_2$ discussed above, simultaneouse retrievals of CH_4, N_2O, NO_2 and H_2O are underway.

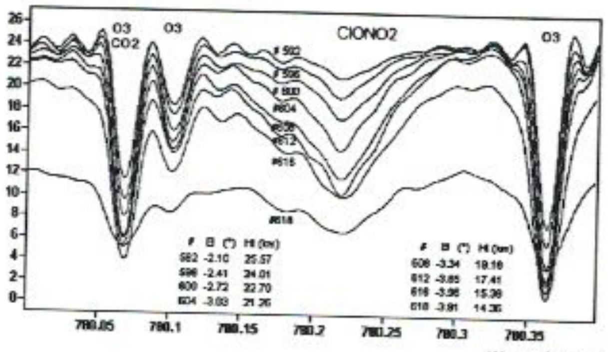

Figure 10: $ClONO_2$ spectra recorded as in Fig. 9. O_3 and CO_2 lines are also contributing in this interval.

7. AKNOWLEDGEMENTS

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