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Oleg I. Korablev[1], Jean-Loup Bertaux[2], Imant I. Vinogradov[1], Yurii K. Kalinnikov[3],
D. Nevejans[4], E. Neefs[4], T. Le Barbu[5,2], G. Durry[5,2]

[1]Space Research Institute (IKI), Moscow, 117997, Russia, oleg.korablev@irn.iki.rssi.ru
[2]Service d'Aeronomie B.P.3 Verrieres le Buisson Cedex F91371 France, bertaux@aerov.jussieu.fr
[3]AFAR, NPO SPURT, 141570, Zelenograd, Moscow Region, Russia, kayuk@aspnet.ru
[4]Belgian Institute for Space Aeronomy, 3 Ringlaan, B1180, Brussels, Belgium.
Dennis.Nevejans@bira-iasb.be
[5]University of Reims, France, thibauld.le-barbu@univ-reims.fr

ABSTRACT

A new concept of a high-resolution near-IR spectrometer consisting of an echelle grating combined with an acousto-optic tunable filter (AOTF) for separation of diffraction orders, is developed for space-borne studies of planetary atmospheres. A compact design with no moving parts within the mass budget of 3-5 kg allows to reach the resolving power $\lambda/\Delta\lambda$ of 20000-30000. Only a small piece of spectrum in high diffraction orders can be measured at a time, but thanks to flexibility of the AOTF electrical tuning, such pieces of spectrum can be measured randomly and rapidly within the spectral range. This development can be used for accurate measurements of important atmospheric gases, such as CO_2 in terrestrial atmosphere, isotopic ratios and minor gases. A spectrometer, based on this principle, SOIR (Solar Occultation InfraRed) is being built for Venus Express (2005) ESA mission. Instruments based on this principle have high potential for the studies of the Earth, in particular for measurements of isotopes of water in the lower atmosphere, either in solar occultation profiling (tangent altitude <10 km), or observing solar glint for integral quantities of the components. Small size of hardware makes them ideal for micro-satellites, which are now agile enough to provide necessary pointing for solar occultation or glint observations. Also, the atmosphere of Mars has never been observed at local scales with such a high spectral resolution. A laboratory prototype consisting of 275-mm echelle spectrometer with Hamamatsu InGaAs 512-pixel linear array and the AOTF has demonstrated $\lambda/\Delta\lambda\approx30000$ in the spectral range of 1-1.7 μm. The next set up, covering the spectral ranges of 1-1.7 μm and 2.3-4.3 μm, and the Venus Express SOIR are briefly discussed.

1. INTRODUCTION

Spectral measurements with high resolution give access to planetary atmospheres when observing from the Earth [1-3]. Very high spectral resolution (sometimes as good as 0.01 cm^{-1}) allows Doppler separation of the spectral lines in the planetary atmosphere from telluric ones, thus enabling to detect and to measure minor constituents and isotopic composition. These measurements, however, are generally full-disk averaged; sometimes a slit of the ground-based spectrometer can be oriented along the equator, and a latitudinal scan can be obtained at the expense of lower spectral resolution and degraded signal-to-noise ratio. Measurements within the strong telluric absorption bands are impossible, making difficult to measure molecules abundant in the Earth's atmosphere.

Therefore, spacecraft measurements at high spectral resolution are of great value in planetary missions. However, all spectrometers used up to recent in deep space missions (for these purposes almost exclusively Fourier transform spectrometers or FTS have been used) [4-5] had at best the spectral resolution of 2.4 cm^{-1} (maximal resolving power of ~800 at short wavelength). It is the apodized spectral resolution of IRIS Michelson interferometer flown on Mariner 9 in 1971, which brought a number of important constraints on the composition of the Mars atmosphere [6]. All other FTS on planetary missions have a typical resolution of 5 cm^{-1}, with the exception of PFS, a FTS flying now onboard Mars Express, which, with unapodized spectral resolution of almost 1 cm^{-1} offers the resolving power in the short wavelength channel superior to 4000 [7]. Among the instruments used to study the atmosphere of the Earth, the achieved spectral resolution is much better ($\Delta\nu$=0.03-0.1 cm^{-1}) [8-9]. But the mass of these state-of-the-art instruments (hundreds of kilograms) prevents them from being sent toward other planets. Moreover, even in the remote sensing of the Earth the tendencies are that large missions requiring many years of preparation become rare. Compact and lightweight instrumentation has more chances to be rapidly flown at small and very small platforms, or like a supplementary payload at, e.g., telecommunication satellites.

The method of solar occultation is very effective for sensitive studies of atmospheric composition and the precision profiling, as demonstrate magnificent results

of ATMOS experiment [10-11]. High brightness of the Sun as the source of light allows to save mass throughout the optical system, because the required etendue is not very high. Canadian satellite SCISAT-1 employs ACE (Atmospheric Chemistry Experiment) based on a compact FTS for the spectral range of 2-14 µm with resolution of 0.025 cm^{-1}. Modern technologies enabled mass reduction to ≈35kg [12].

We have considered a new concept of a compact high resolution system for remote measurements of gaseous composition with characteristic resolution of ~0.1 cm^{-1} (the resolving power of 20000-30000) and within the mass budget of less than 4-5 kg with no moving parts. The implementations of this idea employ the method of solar occultation. Meanwhile, the sensitivity is sufficient for measurements of solar glint (on Earth) and of the solar light diffused from the surface. The system consists of an echelle spectrometer, combined with an acousto-optic tunable filter (AOTF) for separation of diffraction orders. With regards to the studies of planetary atmospheres this approach offers dramatic (an order of magnitude) increase in resolving power that conducts to significant improvement in sensitivity and accuracy. On Mars Express we have already demonstrated operability of the AOTF in deep space missions [13].

Echelle spectrometers are widely used in astronomy, where a crossed dispersion spectrometer became standard high resolution equipment in the visible spectral range. In such a spectrometer several pieces of highly resolved spectrum pattern in different diffraction orders are simultaneously registered at a 2D array detector, being separated along the second coordinate due to the use of an auxiliary low-dispersion element: a prism or a grating. With the development of larger 2D detectors for the IR range, such spectrometers are gradually replacing FTS at the IR telescopes as well. A brilliant example of the IR crossed dispersion spectrometer for space study presents the high resolution channel of VIRTIS instrument, to be flown to the Churumov-Gerasimenko comet on Rosetta mission in 2004 [14]. In crossed dispersion spectrometers a large portion of high resolution spectrum can be acquired in a single exposure, as several inclined lines at the 2D imaging detector. In turn, the maximal number of diffraction orders to be observed simultaneously, is usually limited to 10-15 (the height of the corresponding lines at the detector is proportional to the slit height, and, therefore, to the etendue of the instrument); as a result the resolving power is in trade with spectral coverage. Filtering of the input radiation is required to avoid overlapping of distant diffraction orders. Some echelle instruments, like CSHELL (NASA IRTF at Hawaii) [15], even though possessing the 2D detector, do not use crossed dispersion at all in favor of high slit

and imaging capability. In this case selection of diffraction orders is done by a fitter wheel.

Proposed instrument, employing the AOTF for preliminary selection of diffraction orders, allows to combine the advantages of the very good spectral resolution and a flexible access to virtually any part of the spectrum within the spectral range of a chosen detector. It is possible to align the parameters of the optical scheme so that the spectral coverage would be quasi-continuous. Only one diffraction order can be recorded during one exposure, in exchange on the advantage of having a high slit and imaging potential.

The instrument, combining the echelle spectrometer and the AOTF has been developed in Iowa University [16] for monitoring spectral emission in air and plasma for industrial applications. A mock-up of compact 38-cm spectrometer for the visible spectral range with the performances of 1.5-m spectrometer is described. To our knowledge our design, first reported in [17] is the first dedicated to atmospheric composition, and to space research.

In this paper we will briefly consider scientific targets of a solar occultation high resolution instrument on a planetary orbiter, present first results of this new development, obtained with a principle-demonstration breadboard, and will give some details on the implementation of this principle in SOIR (Solar Occultation InfraRed) experiment working in the spectral range of 2.2-4.2 µm is being prepared for Venus Express ESA mission.

2. SCIENCE OBJECTIVES OF HIGH-RESOLUTION ABSORPTION SPECTROSCOPY

2.1 Venus

On Venus dense atmosphere with opaque clouds located at 45-60 km prevents from deep penetration in solar occultation sounding. High-resolution occultation studies are possible above clouds, in the upper-cloud layer (<90 km) and higher. It allows to plan unique measurements connected to escape of water, and therefore to the evolution of water on the planet. The same issue is also of high significance on Mars [1].

On Venus the ratio of D/H exceed the terrestrial value by factor of ≈100 [2]. Such a high D/H value suggests that an equivalent 3-km ocean could exist on Venus in the past. But while escape of hydrogen is known, escape of deuterium is poorly constrained by observations [18]. It may be zero, if there is a cold trap for HDO in the upper atmosphere of Venus as it exists on Earth. If true, then only 30m of water ever existed on Venus. SOIR will measure HDO profile up to 80-90 km (Fig. 1), characterizing escape of deuterium. At 60 km somewhat

exaggerated SO_2 (assumed as high as 150 ppm at this altitude) contaminates HDO, while one line can still be detected (red arrow). HDO is very well measurable at 60-70 km, in the region where the "cold trap" may exist. In Fig.1 assumed H_2O is 5 ppm; D/H=120 times terrestrial.
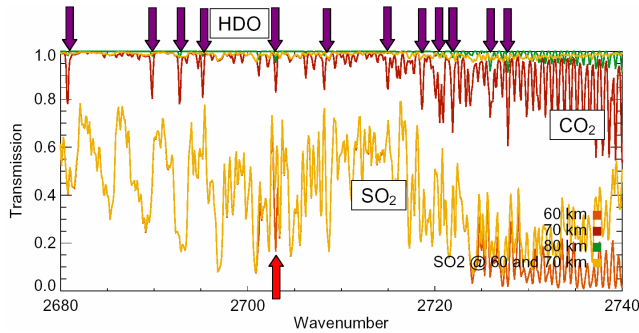

Fig.1 Synthetic spectra of limb transmission for grazing altitudes 60-80 km.

Other scientific targets of SOIR on Venus are: precision H_2O profiling up to ≈105 km; measurements of atmospheric density up to very high altitudes, though complicated due to LTR violation; measurements of CO_2 and H_2O isotopes (besides HDO); measurements of known minor constituents (CO, HF, HCl, SO_2, H_2S, OCS); sensitive search for new minor species (C_2H_2, CH_4, NO, N_2O, H_2CO, HCN and many others).

2.2 Mars

There is a high potential of SOIR measurements on Mars. SOIR could be considered as the return at a qualitatively higher level to the investigation of SPICAM-S solar occultation experiment onboard of unsuccessful Mars 96. We have proposed SOIR for Mars Premier mission orbiter, and will pursue proposing it for any future orbiter opportunities.
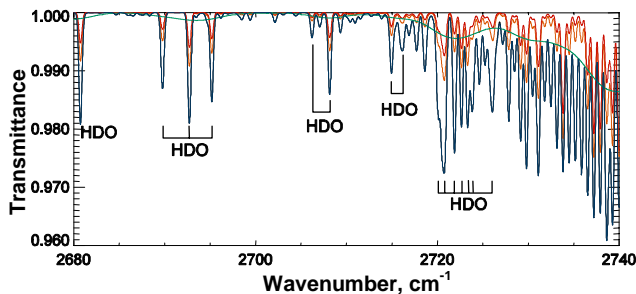

Fig 2. Synthetic spectra of atmospheric transmission of Mars in solar occultation (grazing altitudes 0, 10, and 15 km) for water vapour amount of 10 precip. µm; medium resolution spectre (2 cm^{-1}) is shown for comparison (green curve).

SOIR measurements on Mars address the problem of deuterium escape, similarly as on Venus. We have demonstrated that in tiny Martian atmosphere with law water vapour content high spectral resolution imperatively required for meaningful measurements of HDO (Fig. 2). Besides, SOIR on Mars is capable to measure H2O up to altitudes of 100 km, CO_2 and H_2O isotopes, and to search for yet undetected species such as CH_4, H_2CO, NH3, C_2H_2, HCl, etc.

2.3 Earth

In spite of many high-resolution instrument used and planned for use at the Earth orbit (see section 1) there remains a room for focused observations from small and very small platforms. A hot topic is now the carbon budget calling for precise local measurements of total carbon dioxide abundance in the air. This is the main goal of NASA Orbiting Climate Observatory (OCO) project planned for launch in 2006 [19].

CO_2 total column measurements can be done in nadir or in solar glint configuration. Technical reasons, such as TE-cooled sensitive InGaAs detector suggest to use spectral range of 1-1.7 µm. A spectral interval sufficient to cover non-saturated NIR CO_2 band could be found within a single diffraction order, but tuning with the AOTF to other diffraction orders allows to measure in parallel other important gases, such as O_2 at 1.27 µm to provide airmass reference, and greenhouse H_2O at 1.38 µm and CH_4 at 1.65 µm. OCO employs three echelle spectrometers to cover spectral rages relevant to CO_2, O_2 and H_2O. An instrument with the AOTF will do it with the single spectrometer.

Ground validation of satellite measurements with solar measurements from the surface is required. So far they are possible with large high-resolution FTS. There are few such instruments, and precision CO_2 measurements are difficult because acquiring a spectrum takes a long time and the airmass changes. Far cheaper and compact AOTF-echelle instrument could form a basis of the new ground network for CO_2 monitoring (see Section 5).

3. THE PRINCIPLE OF THE HIGH-RESOLUTION SPECTROMETER WITH AN AOTF

In general words, the principle of the SOIR instrument can be formulated as follows: a combination of the AOTF and any other classical highly-dispersive system.

Most of systems (grating spectrometer, Fabri-Perot interferometer, etc.) dedicated for high-resolution spectral analysis employ in fact two separate systems: main high-resolution system, generally producing numerous overlapping orders, and a secondary system, which isolates one diffraction order (order sorter) or

distributes the orders on the surface of the detector to avoid overlapping (crossed dispersion). In the proposed design the AOTF serves to separate diffraction orders, to choose a single order among them in the desired spectral range. Change of orders is fast (few tens of microseconds), governed by an electrical command with no moving mechanical parts. A scheme, illustrating the order sorting with the AOTF if given in Fig. 3.
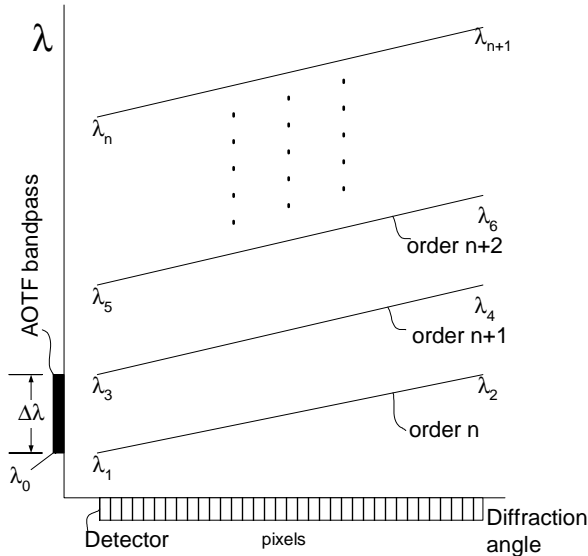

Fig. 3. The principle of echelle diffraction orders separation by AOTF

An example optical scheme of such system is presented in Fig. 4. Main dispersive system consists of autocollimation echelle grating spectrometer. Echelle grating is illuminated with a parallel beam from collimating mirror which is used for both incidence and diffracted beams. The light is dispersed in the plane perpendicular to the grating grooves and the resulting spectrum is analyzed with a linear array detector. The slit and the detector are separated in the vertical plane (parallel to grating grooves).

The main equations, describing this classical scheme are as follows: each point in the detector plane, corresponding to diffraction angle i' satisfies to grating equation

$$\sin i + \sin i' = k\,\lambda_k(1/a), \qquad (1)$$

where i and i' – incidence and diffraction angles, λ_k- wavelength, $1/a$- number of grooves per cm, and k – diffraction order. Angular dispersion

$$D = \frac{di'}{d\lambda} = \frac{k}{a\cos i'} = \frac{\sin i + \sin i'}{\lambda\cos i'} \qquad (2)$$

depends mainly from diffraction angle, and the ratio k/a can be chosen independently on other parameters. Free dispersion range (FSR), i.e. the range $\Delta\lambda$, without overlapping of orders depends on the number of grooves:

$$\Delta\lambda = \frac{\lambda}{k} = \frac{\lambda^2}{a(\sin i + \sin i')} . \qquad (3)$$

In autocollimation the grating blaze angle $\theta = i \approx i'$, and

$$\Delta\lambda = \frac{\lambda^2}{2a\sin\theta}, \qquad (4)$$

or, expressed in wavenumbers

$$\Delta\nu = \frac{1}{2a\sin\theta} . \qquad (5)$$

To optimize the parameters of the echelle-AOTF spectrometer on one needs to align the following parameters: FSR, AOTF bandpass, and the spectral interval, corresponding to the angular size of the detector. FSR (Eq. 5) does not depend on the wavelength, that allows to align it in the entire spectral range with the AOTF bandpass which, expressed in cm^{-1}, is also nearly independent on λ. But the spectral interval, corresponding to the detector is proportional to λ (Eq. 2). As a result full optimization in a wide spectral range is not possible, e.g., for shorter wavelengths only a central part of the detector can be used, while for longer wavelengths the edges of the spectrum are lost.

The resolving power is determined by the angular dispersion (Eq. 2), focal distance of the spectrometer F, and the pixel size of the detector:

$$\frac{\lambda}{\Delta\lambda} = \frac{F(\sin i + \sin i')}{\Delta l\cos i'} = \frac{2F}{\Delta l}\tan\theta, \qquad (6)$$

or, taking into account the detector sampling

$$\frac{\lambda}{\Delta\lambda} = \frac{F}{\Delta l}\tan\theta . \qquad (7)$$

In the IR the resolving power can be readily limited by diffraction, therefore the focal ratio of the spectrometer should be aligned with (Eq. 7). On the other hand, even with very small number of grooves per mm, the maximal resolving power of the grating generally exceeds Eq. 7 and is not a limiting factor.

The choice of parameters of the echelle grating is critical. Blaze angle defines dispersion and resolution, and the number of grooves per millimeter defines FSR.

To obtain quasi-continuous coverage one needs to employ very high diffraction orders. In the IR this requires very small number of grooves per mm/ of the order 4-8 gr/mm. Such a distant ruling is available only upon custom request, and their fabrication may require a substantial cost for non-recurring engineering. Note, that for some applications, in particular for the visible and near IR range standard ~20 gr/mm echelles might be acceptable, but nearly-continuous coverage might be realized on with small number of grooves per mm.

4. FIRST IMPLEMENTATION: A LABORATORY MOCK-UP

To demonstrate the principle of the AOTF-echelle spectrometer we have assembled a fully functional laboratory model of the spectrometer (Figs. 4 and 5).

As shown in Fig. 4, a collimated light beam with an aperture up to 30 mm from a test source or the Sun is collected by an entrance telescope 1 (15° off-axis parabolic mirror, focal length 155 mm), and focused into the plane of a field diaphragm 2, 0.3 mm wide. This diaphragm is located at the focal plane of a short-focus microscope objective lens 4 (9$^\times$, NA=0.22). A quasi-parallel light beam (divergence <0.5º) with an aperture of 3×3 mm^2 is directed to the AOTF. We have used an adapted telecommunication AOTF model, a narrow-aperture, quasi-collinear AOTF device. As a result of the acousto-optic interaction, light at selected wavelength is deflected from the main beam at the AOTF output by +2° and –2° in the acoustic wave propagation plane, for the two orthogonal polarization components of the light. One of these filtered and deflected light beams is focused by means of a short-focus microscope objective lens 7 (8$^\times$, NA=0.2) onto the entrance slit 8 of the spectrometer. The filtered and deflected light wave of another polarization is folded by a flat mirror 13 into the entrance aperture ∅ 1 mm of a InGaAs photodiode 14 (Hamamatsu) to monitor AOTF operation. Undiffracted light is directed into a light trap 15, by means of the same flat mirror 13. A supplementary (f=170 mm) lens 6 forms the pupils of the AOTF output beams in the proximity of the objective 7, at the photodiode 14, and in the light trap 15, providing clear separation of the beams, diverging at a small angle.

Echelle spectrometer consists of a slit 8, 50 μm wide, a flat mirror 9, a concave mirror 10 (15° off-axis parabolic mirror, focal length 275 mm), an echelle grating 11 (Richardson Grating Laboratories, 24.355 gr/mm, 70° blaze angle, 100×50×16 mm^3 substrate size), InGaAs 512-pixel linear array detector 12 (Hamamatsu C8061 detector head with G8163-512S linear array, 25×500 μm^2 pixel size, 12.8×0.5 mm^2 active area). The mirror 10 serves as an autocollimating

objective in Littrow mounting. In the focal plane of the main mirror the incident and diffracted beams are separated vertically by 6 mm. A small value of this vertical shift provides for a reasonably small off-axis aberrations. Resulted distortions are then reduced to small variations of amplitude and position of spectral peaks. The slit width is chosen to be as twice large as the array pixel width, providing Nyquist sampling. The spectral sensitivity of detector limits the spectral range to 1-1.65 μm.
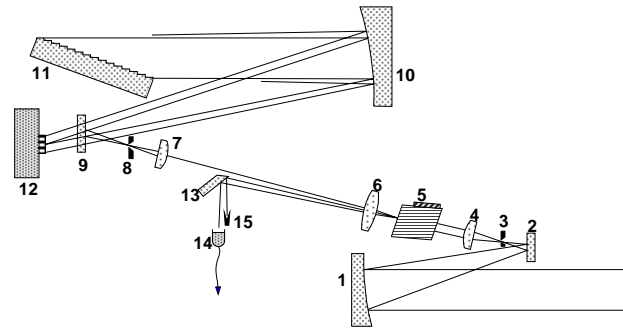

Fig. 4 The optical scheme of the spectrometer: 1- entrance telescope (off-axis parabolic mirror), 2, 9, 13- flat mirrors, 3- field diaphragm, 4- collimator short-focus lens, 5- AOTF, 6- additional long-focus lens, 7- focusing short-focus lens, 8- slit of the spectrometer, 10- spectrometer collimator (off-axis parabolic mirror), 11- echelle grating, 12- linear InGaAs array, 14- InGaAs photodiode: auxiliary low-resolution detector, 15- light trap for undiffracted light.
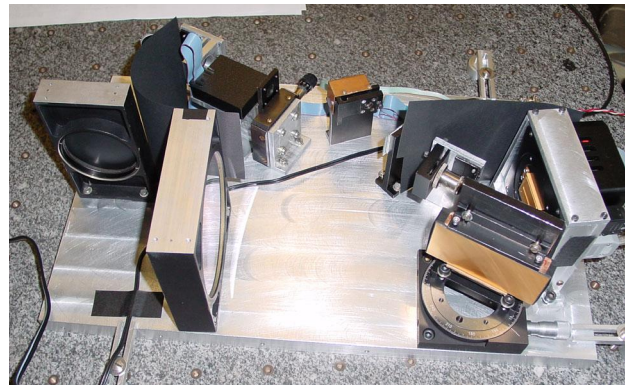

Fig. 5 The layout of the echelle-AOTF spectrometer bread board.

RF drive signal for the AOTF piezotransducer is provided by DDS/DAC synthesizer AD9851, tunable from 80 to 40 MHz. RF synthesizer is controlled via parallel port of a PC. The linear array detector is controlled through a specialized PC-plugged Hamamatsu SA1400 interface board.

5. MEASUREMENTS

The spectral resolution the spectrometer was first verified with a He-Ne 1152 nm laser (Fig.6). It is determined by the array detector pixel pitch and the entrance slit width, and amounts to $\approx 3 \times 10^4$ at this wavelength. Fig. 6 demonstrates that the spectral resolution of the HR spectrometer channel is close to 2 pixels, in accordance with the slit width. Therefore the aberrations of the spectrometer are small. Theoretical resolving power of the grating is 1.6×10^5, leaving enough margin.
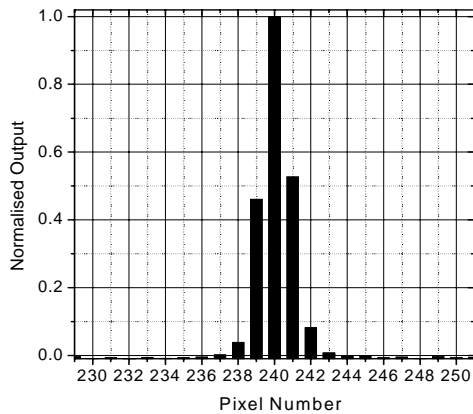

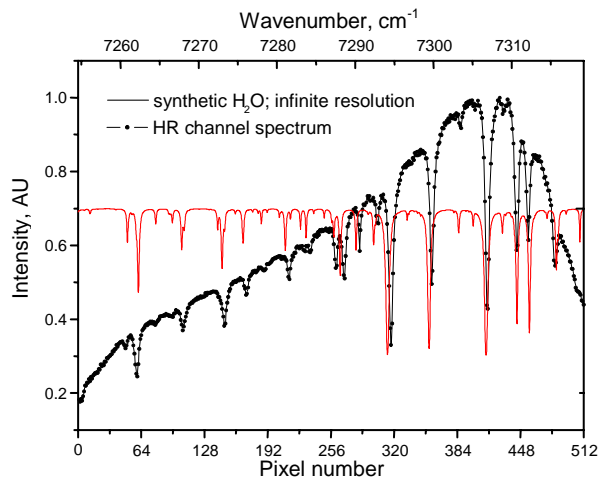Fig.6. Spectrum of the He-Ne laser 1152 nm line, demonstrating the resolving power of the spectrometer.

Fig.7. Water vapor absorption spectrum at 1.39 µm for optical path of 2 m in the laboratory air, resolved by the spectrometer, compared to the synthetic transmission spectrum of H_2O.

We recorded the absorption spectrum of water vapor in the laboratory air. A continuous 75 W Xenon lamp (Oriel Instruments) illuminated the entrance aperture of the spectrometer. Its light passed the distance of ~ 2 m in the laboratory air, including the internal path in the

spectrometer. At 1.39 µm a shallow emission peak of the Xenon lamp falls into the strong water vapor absorption band, as shown in Fig.7. The resolving power of 3×10^4 allows clear resolution of the H_2O absorption lines and their profiles. The FWHM of the H_2O absorption lines is estimated to be near 0.1 nm, or 0.5 cm^{-1}, a typical value for normal conditions. A synthetic H_2O spectrum at 2 m absorption path and normal conditions computed for an infinite spectral resolution is also shown in Fig.7 for comparison.
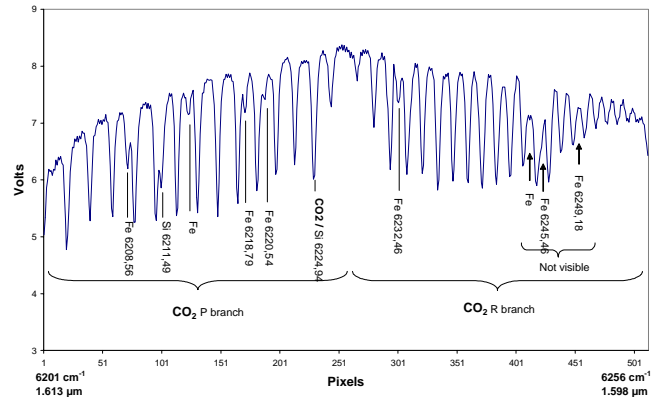

Fig.8. Solar spectrum measured with SOIR prototype, showing a portion of CO_2 1.6-µm band.

Solar measurements from the ground with first SOIR prototype have confirmed its capability to measure accurately important atmospheric gases. In Fig. 8 we present one raw spectrum from a series taken when pointing SOIR to the Sun through the Earth atmosphere in Reims, France on 30 Jan 2004 at cloudy sky. Exposure time was 6 s. It demonstrates clearly resolved CO_2 and solar lines.

6. NEXT SET-UP

We have demonstrated the functional laboratory model of a compact (*f*=275 mm) echelle spectrometer achieving the resolving power of $\lambda/\Delta\lambda \approx 30000$. Further development consists of building of new "fieldable" prototype of an instrument for solar atmospheric measurements. Two versions of the spectrometer are in progress, a set-up for the spectral range 1.-1.7 µm, basically for CO_2 and related measurements (see section 2.3), an improvement of the first mock-up, an another one for the spectral range of 2.5-4.5 µm. Both schemes employ a custom AOTF devices, with the bandpass adapted for required FSR. Catalogue echelle gratings are used. Short-wavelength version employs the Hamamatsu InGaAs linear array, and the long-wavelength one will use a 2D CdHgTe (CMT) SOFRADIR detector with an integrated cooler device, similar to that used in for SOIR Venus Express (see below).

7. SOIR: THE EXPERIMENT ON ECHELLE-AOTF SPECTROMETER FOR VENUS EXPRESS

SOIR (Solar Occultation InfraRed) experiment was proposed as a light-weight high-resolution solar occultation instrument to study the composition and structure of the atmosphere of Venus above clouds. It was accepted onboard in 2001 as an extension of SPICAV instrument with common mechanical envelope and shared electronic block. Presently SOIR for Venus expressed is being built by Belgian industry (OIP Sensor Systems) under responsibility of BIRA-IASB funded via PRODEX contract.

Optical design of SOIR is by OIP Sensor Systems; electronics designed by BIRA-IASB. Main features of the instrument are

– 2D CMT detector from SOFRADIR, France (see Table 1)
– Custom AOTF from AFAR, Russia (QM delivered)
– Custom echelle grating from Bach Research, Boulder, U.S.A. (see Table 2)

It is planned that a complete flight model of SOIR will be delivered for testing in May 2004.

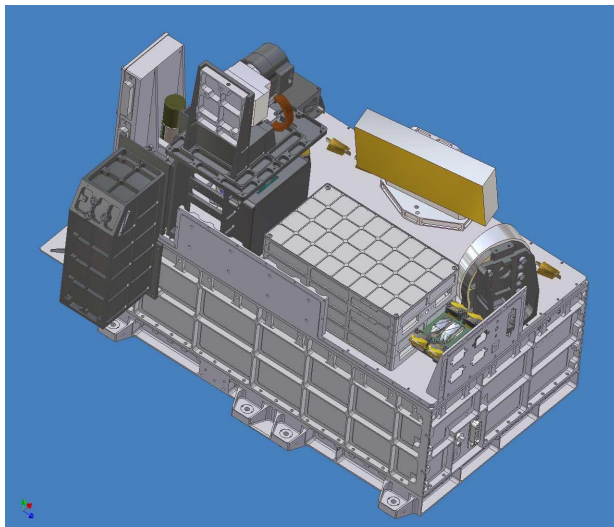The layout of the SOIR mounted on the SPICAV is presented in Figs. 9 and 10.

Fig. 9. SOIR-SPICAV assembly. The cover of SOIR is not shown. The elements clockwise: solar entry, detector-cooler assembly, grating, collimator mirror, electronics.
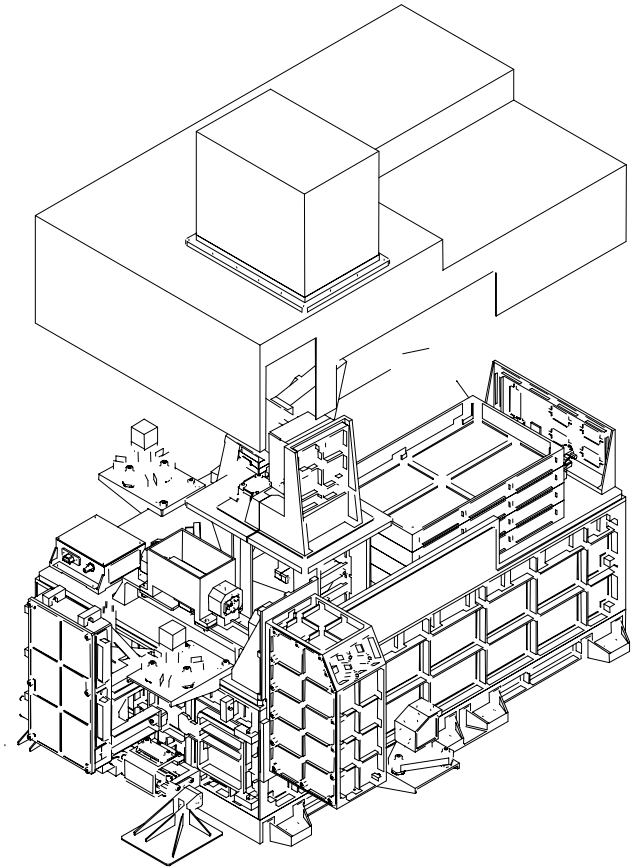

Fig. 10. SOIR-SPICAV assembly "exploded" from different vantage point. The elements not visible in Fig.9 are the AOTF, AOTF amplifier, alignment cube and the cover. At the front side there is a multiple shutter of SPICAV optical entries.

Table 1 SOIR IR integrated detector cooler characteristics

Detector Manufacturer	SOFRADIR, France
Detector model	Modified IDMM067
IR detector material	Mercury Cadmium Telluride ($H_gC_dT_e$)
Covered IR wavelength range	1.66 to 4.2 μm (FWHM)
Operating temperature	90 - 110 K
Pixel configuration	2-D array organized as 320 columns by 256 rows Programmable windowing
Pixel size	30 μm x 30 μm
Output level	1.6 (no light) to 4.4 V (full well)
Linearity (typical)	+/- 1 % between 25 and 92 % of full well +/- 2 % between 10 and 98 % of full well
Gain setting	0.7 or 2.1 pF integration capacitor
Responsivity (measured over complete wavelength range)	Typical 76 V/nW per pixel @ 20 msec integration time and gain setting = 0.7 pF

Read-out speed	1 to 6 MHz for single output
Integration time	Minimum 3 μsec Acceptance tested at 20 msec
Detector mounting	Mounted in dewar with f/4 cold screen
Integrated microcooler model	K508, modified for space applications
Microcooler manufacturer	RICOR, Israel
Steady state cooling power (begin of life)	4.1 W typical @ 24 V supply voltage (in 20° C air)
Pre-cooling power (begin of life)	9.4 W typical @ 24 V supply voltage (in 20° C air)

Table 2 SOIR echelle grating characteristics

Wavelength range	2.2 to 4.3 μm
Diffraction orders	100 to 200
Steep edge angle = blaze angle (Θ)	63.43º = arctan(2)
Number of grooves per mm	4
Groove spacing	250 μm
Total number of grooves (N)	568
Ruled area	142 x 56 mm^2
Blank dimensions	150×60×25 mm^3
Blank material	Aluminium 6061-T6
Coating material	Au

8. ACKNOWLEDGEMENTS

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