Description, accessibility and usage of SOIR/Venus Express atmospheric profiles of Venus distributed in VESPA (Virtual European Solar and Planetary Access)

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L. Trompet [a,*], Y. Geunes [a], T. Ooms [a], A. Mahieux [a,b], V. Wilquet [a], S. Chamberlain [a], S. Robert [a], I.R. Thomas [a], S. Erard [c], B. Cecconi [c], P. Le Sidaner [d], A.C. Vandaele [a]

[a] Royal Belgian Institute for Space Aeronomy, 3 av. Circulaire, 1180 Brussels, Belgium
[b] Fonds National de la Recherche Scientifique, Brussels, Belgium
[c] LESIA, UMR8109, Observatoire de Paris, CNRS, PSL Research University, UPMC, Univ. Paris Diderot, 5 pl. J. Janssen 92195 Meudon, France
[d] DIO, UMS2201, Observatoire de Paris, CNRS, PSL Research University, 61 Av de l'Observatoire, 75014 Paris, France

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ABSTRACT

Venus Express SOIR profiles of pressure, temperature and number densities of different constituents of the mesosphere and lower thermosphere of Venus are the only experimental data covering the 60 km to 220 km range of altitudes at the terminator of Venus. This unique dataset is now available in the open access VESPA infrastructure. This paper describes the content of these data products and provides some use cases.

1. Introduction

The Venus terminator is a region of great interest as a transition between the hot dayside and the cold nightside of the Venus atmosphere (Keating et al., 1980) (Keating et al., 1980). Moreover the mesosphere (70–95 km) and lower thermosphere (95–150 km) are poorly known regions where few measurements have been performed. These have been summarized in the Venus International Reference Atmosphere (VIRA) which was compiled by Kliore et al. (1985) and later updated by Moroz and Zasova (1997) who considered several missions like VEGA 1 and 2 or the Galileo fly-by in 1990. The structure (total density and temperature) of the Venusian atmosphere was updated by Zasova et al. (2006), however nothing similar was ever done for the composition. Since then and until recently, the Venus Express mission yielded a wealth of new information on the Venus atmosphere, from the surface up to the highest layers of the atmosphere. In particular a series of spectrometers sounded the atmosphere to derive new data on the structure but also on the composition. Particularly the SOIR instrument, which is part of the SPICAV suite, is sensitive in the infrared spectral region. The data set which is described in this paper, has been collected and compiled for the first time from several individual analysis of SOIR data.

SOIR (Solar Occultation in the InfraRed) (Nevejans et al., 2006) was an infrared spectrometer on-board the Venus Express (VEx) orbiter of the European Space Agency (ESA) which probed the Venus upper at the terminator (Titov et al., 2006). It was sensitive in the 2.2–4.3 μm (2200–4370 cm^{-1}) spectral range and used an echelle grating in front of which an Acousto-Optical Tunable Filter (AOTF) was placed (Nevejans et al., 2006). This AOTF was used to select the spectral interval to be measured, which was chosen to correspond to one of the diffraction orders of the echelle grating.

SOIR made solar occultation observations all along the mission of VEx around Venus, from May 12, 2006 till November 27, 2014. SOIR scanned the light coming from the Sun and passing through the atmosphere of Venus at the terminator as illustrated in Fig. 1. During one solar occultation observation, SOIR could scan up to four different diffraction orders providing eight different sets of spectra, because two spectra were recorded simultaneously on two different detector areas. A set of spectra represent thus a series of spectra obtained at different tangent altitudes in one chosen spectral interval for one of the two detector areas. Each measured spectrum corresponds to one tangent altitude at the terminator of Venus while typically a set of spectra covers the 60 km to 220 km range of tangent altitudes. The averaged projected vertical field of view at the terminator of Venus for all observations made by SOIR when crossing the tangent point of 65 km is 5.82 km with a standard deviation of 5.0 km.

The profiles presented here have been produced using the ASIMAT program described in Mahieux et al. (2015a, 2010, 2012) and Vandaele

* Corresponding author.
E-mail address: loic.trompet@aeronomie.be (L. Trompet).

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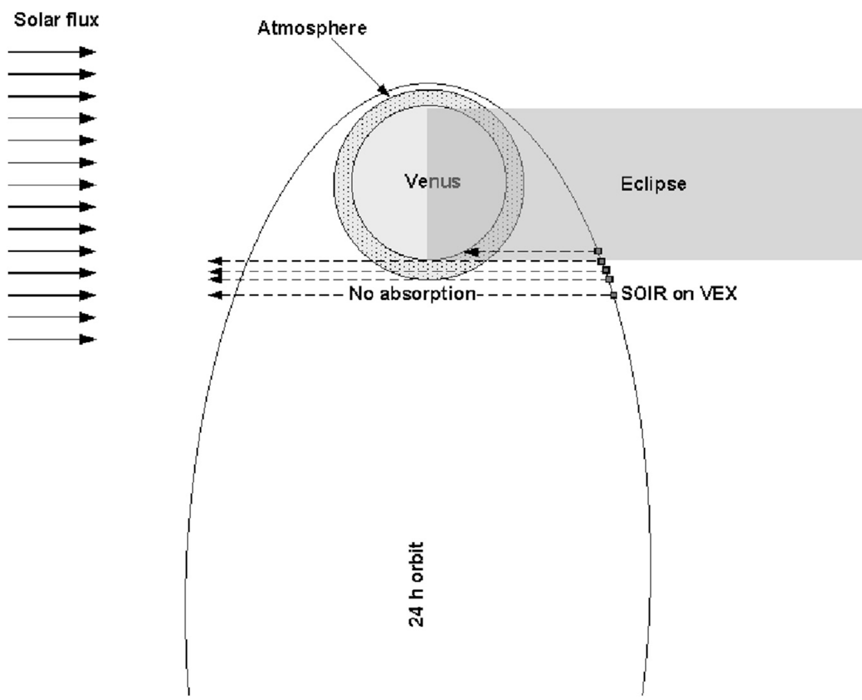

Fig. 1. SOIR scanned the atmosphere of Venus at the terminator using a solar occultation geometry.
This figure has been reproduced from Nevejans et al. (2006).

et al. (2015). We will give here only a short description of the code. ASIMAT is an iterative algorithm working in a two-step procedure summarized in Fig. 2.

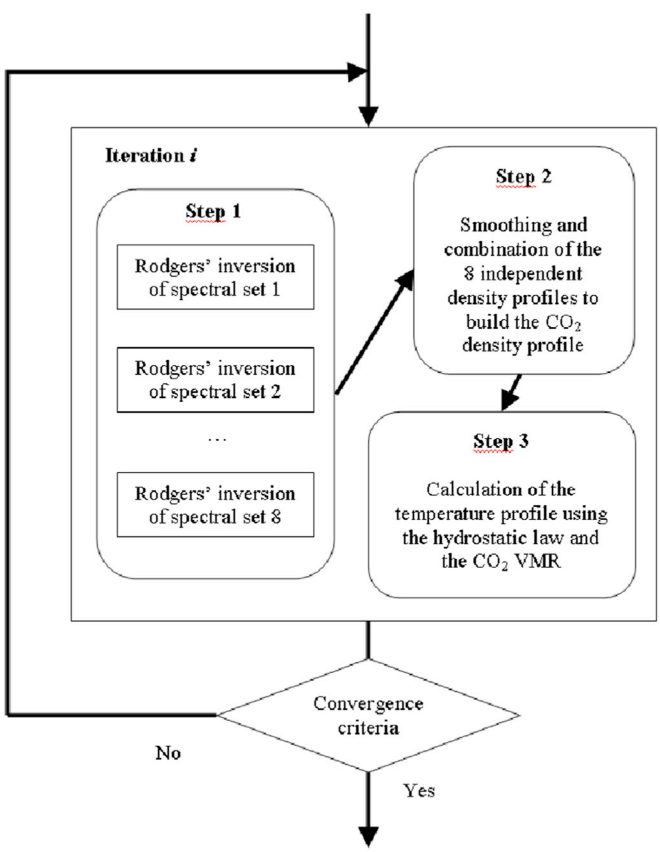

Fig. 2. Working principle of the ASIMAT program to derive profiles from the spectra of SOIR.
Figure reproduced from Mahieux et al. (2012).

In the first step of each iteration, the different sets of spectra are inverted for the species that can be retrieved, i.e. which present absorption lines in these spectra. The method is based on a Bayesian algorithm (Rodgers, 2000) in an onion peeling frame. This approach consists to separate the atmosphere of the planet into different layers. Each layer is characterized by its pressure and temperature, which allows the calculation of the Line by Line absorption cross section of each species in that layer. The problem is then transformed into a non-linear equation system, where the densities of each species in each layer (i.e. the profiles) are the unknowns. The retrieval method is applied in an independent way on the different sets acquired during one solar occultation observation. The extent of the profiles is limited at low altitudes by absorption lines saturation due to the long light path in the atmosphere, and at high altitudes by the too weak absorption with respect to the spectral noise. Each profile can thus have different extensions in altitude, depending on the atmosphere conditions and the diffraction orders scanned during each orbit.

In the second step, the profiles generated independently from the different sets of spectra are combined for the same molecular species on a 1 km constant altitude step grid: the resulting profile is obtained using an error weighted linear moving average, which has a default width of ± 1 scale height centred around each point of the final altitude grid (hereafter called smoothing factor). The uncertainty is also calculated during this step.

These two steps are made for all species that can be fitted. If CO_2 is among the fitted species, a third step is carried out during which the temperature profile and its associated uncertainty are calculated assuming hydrostatic equilibrium (Mahieux et al., 2015a, 2010, 2012).

The iterative procedure stops when all the profiles of the fitted species, including the temperature profile if CO_2 was among the fitted species lie within the uncertainty of their corresponding profile at the previous step.

The following species have been presented and studied in several publications: CO_2 (Mahieux et al., 2010, 2012, 2015b), CO (Vandaele et al., 2015, 2016a), $H^{35}Cl$, $H^{37}Cl$, HF (Mahieux et al., 2015c), SO_2 (Mahieux et al., 2015d), H_2O, HDO (Fedorova et al., 2008) and the aerosols (Wilquet et al., 2009, 2012). Vandaele et al., (2016b) gives an

Table 1
Number of vertical profiles accessible through the *soir* database.

Species	Number of vertical profiles
CO_2	120
CO	215
$H^{35}Cl$	159
$H^{37}Cl$	163
HF	57
SO_2	92

overview of all the profiles available (see Table 1 in (Vandaele et al., 2016b)). The data of these profiles are accessible online through the VESPA (Virtual European Solar and Planetary Access) (Erard et al., 2014) search interface at http://vespa.obspm.fr. More information about SOIR and the data provided can be found in the Venus dedicated website of the IASB-BIRA Planetary Aeronomy Division (http://venus.aeronomie.be).

The SOIR spectra at PSA level 2 and PSA level 3 are already accessible through ESA's Planetary Science Archive repository in PDS3 format at http://www.cosmos.esa.int/web/psa/venus-express. Level 1 data correspond to raw decompressed files (Level 0) and are not present in the PSA data base. The PSA level 2 data contains spectra corrected for the non-linearity of the detector. It contains the spectra in detector's pixel numbers and Analog-Digital Units (ADUs). PSA level 3 data are corrected for the bad pixels; the pixel numbers are converted into wavenumbers and the ADUs are converted in transmittances. The reader can find more information about the calibration of SOIR spectra in Mahieux et al. (2008), Vandaele et al. (2013) and Trompet et al. (2016). Note that, in a near future, ESA will allow the accessibility of these data through the VESPA infrastructure.

2. Description of SOIR's profile files

Each file distributed in VESPA contains one single profile of a given species obtained during a specific observation described by the orbit number during which the observation was carried out. The name of a file is then given by: OrbitXXXX.Y_AAA_B.ZZZ, where *XXXX* is the orbit number, *Y* is the orbit number case, *AAA* is the name of the species, *B* is a number which is related to the isotopologue of the species *AAA* and *ZZZ* is the format of the file.

The use of a supplementary number *Y* is necessary to characterize the different measurements that can be made during a single orbit. For example, for orbit 2850 of VEx (08/02/2008), 3 measurements were made: the two first are solar occultation measurements referenced by 2850.1 and 2850.2, followed by one measurement dedicated to calibration referred to as 2850.3.

SOIR spectral resolution was good enough to resolve the rovibrational absorption structure of the vibrational bands Mahieux et al. (2015b). When the density of the species was derived using concurrently absorption bands of several isotopologues (in the present case, only for CO_2, CO and SO_2, see for example Mahieux et al. (2012) and Vandaele et al. (2015) and 2016 (Vandaele et al., 2016a)), *B* is fixed to 0. Otherwise, *B* takes the value of the isotopologue used for the determination of the density, following the isotopologue ID number (*Iso* parameter) from HITRAN 2012 (Rothman et al., 2013): *1* for the most abundant isotopologue on Earth; *2* the following next most abundant isotopologue, etc. Note however that the density corresponds to the Earth mean isotopic ratio of the species, i.e. taking into account the relative isotopic ratios of all isotopologues, again using the values specified in HITRAN 2012 (Rothman et al., 2013). These isotopic ratios have not been corrected for Venus except for HDO. Bertaux et al. (2007) mentioned a variable isotopic ratio with respect to the altitude.

Hence, the name of the species in the files can thus be *CO2_0*, *CO_0*, *H2O_1* (for H_2O, excluding HDO), *H2O_4* (for HDO), *HCL_1* (for $H^{35}Cl$), *HCL_2* (for $H^{37}Cl$), *HF_1*, *SO2_1* or *AERO* (for aerosols).

The profiles of SOIR have been released in two different formats for the convenience of the user. The file extension "*ZZZ*" is "*h5*" for HDF5 files and "*xml*" for VOtables (version 1.2 – for more information see IVOA standard documentation http://www.ivoa.net). The HDF5 file format is the internal format used in the Planetary Aeronomy Division at IASB-BIRA. It has been chosen for efficient read/write operations. In addition to HDF5 files, VOtables are also provided. These files are convenient to read with VO tools like TOPCAT from the University of Bristol, UK (Taylor, 2005) and directly available through VESPA search interfaces.

The content of the HDF5 files is separated under different groups (Science, Geometry, Observation and Reference), which also contain the ancillary parameters needed for the full interpretation of the profiles. The profiles are in the *Science* group: total pressure in mbar, the temperature in Kelvin, the total density in cm^{-3}, the density of the species in cm^{-3} and the corresponding VMR for ten smoothing factors as well as the errors on all these quantities. The other groups contain other useful data like the time of the observation, the attitude of the spacecraft, the coordinates of the profile, etc. The corresponding altitudes, latitudes and longitudes can be found in the *Geometry* group.

The VOtables contain the same data as the *Science* group of the HDF5 files in addition to the altitudes.

It should be noted that the density and the VMR profiles are given for ten different smoothing factors (i.e. the window width used for the moving average introduced in Section 1) from 0.1 to 1. The papers released by the Planetary Aeronomy Division of IASB-BIRA mostly used a smoothing factor of 1 (Mahieux et al., 2015a, 2010, 2012, 2015b, 2015c, 2015d). But the smoothing factor used for HCl in Mahieux et al. (2015c) is 0.4 and the smoothing factor for CO is 0.1 in Vandaele et al. (2015) to avoid smoothing out real structures present in the profiles. Remember also that the scale heights are different for each species as they are dependant of the molar mass.

3. Description and accessibility of the *soir* database

Each of these files is described using metadata recorded in a database called *soir*. The metadata are the EPNcore (version 2) parameters required for compatibility with the Europlanet Table Access Protocol (EPN-TAP), a flavor of TAP, which was developed by the International Virtual Observatory Alliance (IVOA). The EPN-TAP server framework is DaCHS (Data Center Helper Suite) (see documentation at http://docs.g-vo.org/DaCHS/). Amongst these parameters, the *granule_uid* is the name of the file, *granule_gid* is the name of species and *obs_id* is the orbit, all of them as described in Section 2. Each file is characterized by a *spatial_frame_type* in our case chosen as *body*, i.e., the coordinate *c1*, *c2*, *c3* from the EPNcore parameters are, respectively, the longitude, latitude and altitude of the profile. A *thumbnail_url* is also provided in the metadata for a quick view to the density profile of the species. Following the EPNcore standard, some EPNcore parameters are not provided as they do not apply for SOIR profiles.

The database contains a view called *epn_core* that provides the EPNcore parameters. This view is accessible through a TAP query to a EPN-TAP data service called *BIRA-IASB TAP*. This data service has been registered in the IVOA registry and the soir. epn_*core* view is thus directly accessible to any search interface of the VESPA infrastructure. The data are also accessible by any visualizing tool (like TOPCAT) through the Simple Application Messaging Protocol (SAMP - see IVOA standard documentation http://www.ivoa.net/Documents/DocStd) developed by IVOA.

Table 1 shows the number of different vertical profiles for each species accessible through the *soir* database. This table contains the numbers for the species already accessible. The profiles of H2O, HDO and aerosols will be made available in the *soir* database later.

4. SOIR database use cases

The following examples were made using TOPCAT. This tool can be used to have a quick look at the metadata as well as at the data of the VOtables.

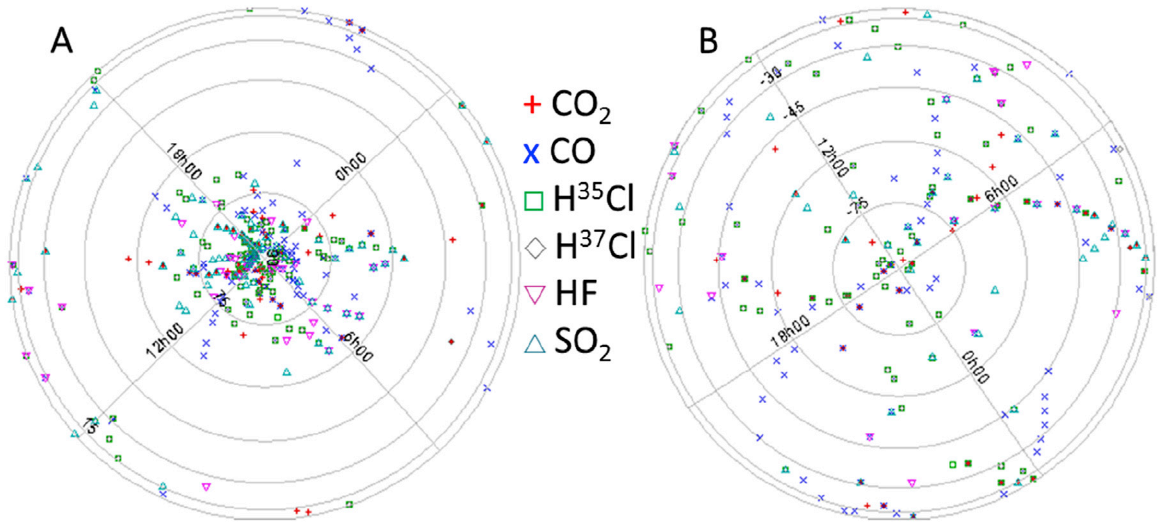

Fig. 3. Positions on the surface of Venus of all the vertical profiles accessible through the *soir* database. Panel A is the north atmosphere and panel B is the south atmosphere.

By loading the metadata from soir. epn_*core* in TOPCAT, a lot of different kind of plots and selection of data can be made. The longitude and latitude of all the measurements made by SOIR around Venus can be plotted using the "sky plotting window" as shown on Fig. 3. As we can see, the orbit of VEx implied that most of the measurements were made close to the pole in the Northern hemisphere. More regularly spaced measurements were carried out in the Southern hemisphere.

TOPCAT can also be used as quick plotting tools to plot 2D or 3D plots of the data contained in the VOtables (e.g. the altitude with respect to the density and the temperature). Thumbnails showing the density of each species with respect to the altitude can be directly seen on the VESPA page dedicated to SOIR profiles.

Fig. 4 shows several plots of the number density of CO_2 (Panel A), CO (Panel B), $H^{35}Cl$ (Panel C) and $H^{37}Cl$ (Panel D) with respect to the

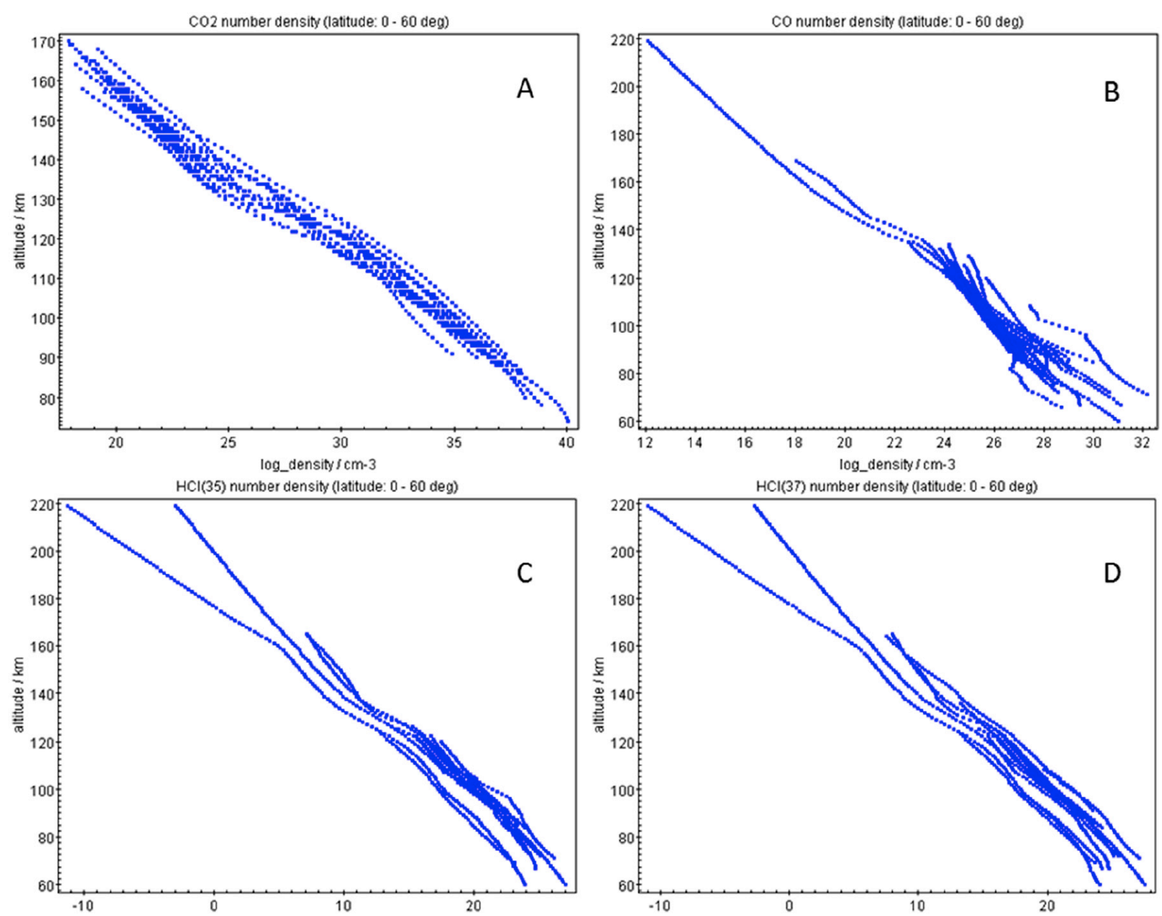

Fig. 4. Number density profiles for CO_2 (panel A), CO (panel B), $H^{35}Cl$ (panel C) and $H^{37}Cl$ (panel D) located between 0 and 60° of latitude (Northern hemisphere). For each species, the corresponding plot contains all vertical profiles retrieved and accessible through the *soir* database.

altitude for all measurements made between 0° and 60° of latitude North using a smoothing factor of 1. The corresponding plots in the dedicated papers can be found in Fig. 3A from the paper of Mahieux et al. (2015c) (Mahieux et al., 2015a) for all latitudes for CO_2; in Fig. 2 from the paper of Vandaele et al. (2016) (Vandaele et al., 2016a) for 0–30° and 30–60° of latitude North for CO; and in Figs. 3A and B of Mahieux et al. (2015b) (Mahieux et al., 2015c) for $H^{35}Cl$ and $H^{37}Cl$ respectively.

5. Upcoming

The profiles for H_2O, HDO and aerosols will be soon included in the database. The data in the files will be slightly different for the aerosols as they will contain the optical depth (τ) and the local extinction (β) instead of the pressure, the total density and the logarithm of the density of the species.

An improved method for the determination of SOIR solar transmittances has been developed and applied to all observations performed by the instrument during the complete duration of the mission (Trompet et al., 2016). This new method aims to normalize more accurately the spectra of the atmosphere of Venus to the solar spectrum. These data have been delivered to ESA and will soon be injected into the PSA archive. In parallel, the retrieval of all densities and temperatures has been restarted considering these new transmittances. Once finalized and validated, these new profiles will be distributed in VESPA.

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