

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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Abstract

Venus Express SOIR profiles of pressure, temperature and number densities of different constituents of the mesosphere of Venus are now available in the VESPA infrastructure. This paper describes the content of these data products and provides some use cases.

1. Introduction

SOIR (Solar Occultation in the InfraRed) [1] is an infrared spectrometer on-board the Venus Express (VEx) orbiter [2] of the European Space Agency (ESA). It is sensitive in the 2.2 to 4.3 μm (2200 to 4370 cm^{-1}) spectral range and used an echelle grating in front of which an Acousto-Optical Tunable Filter (AOTF) was placed for the selection of the order, i.e. the spectral interval corresponding to the diffraction order of the echelle grating. During a single observation, SOIR can scan up to four different diffraction orders giving four different sets of spectra. SOIR made solar occultation observations all along the mission of VEx around Venus, from May 12, 2006 till November 27, 2014.

The profiles presented here have been produced using the ASIMAT program described in Mahieux et al (2015,2012,2010) [3-5] and Vandaele et al. (2015) [6]. We will give here only a short description of the code. ASIMAT is an iterative algorithm working in a two-step procedure. In the first step of each iteration, the sets of spectra are inverted using a Bayesian algorithm (Rodgers (2000) [7]) in an onion

peeling frame. 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 orders scanned during each orbit.

In the second step, the profiles generated from the different sets of spectra are combined for the same molecular species on a 1 km constant altitude step grid. For each retrieved species, the resulting profile is combined using an error weighted linear moving average, which has a default window of ± 2 scale heights. The uncertainty is also calculated. If CO₂ is among the fitted species, the temperature profile and its associated uncertainty is calculated assuming the hydrostatic equilibrium [3-5].

The iterative procedure stops when all the profiles of all fitted species, including the temperature profile if CO₂ 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: CO₂ [4, 5, 8], CO [6, 9], H³⁵Cl, H³⁷Cl, HF [10], SO₂ [11], H₂O, HDO [12] and the aerosols [13, 14]. Vandaele et al. 2015b [15] gives an overview of all the profiles available. The data of these profiles are accessible online through the Venus dedicated website of the IASB-BIRA Planetary Aeronomy team (<http://venus.aeronomie.be>) and they are now also accessible through the VESPA (Virtual European Solar and Planetary Access) [16] search interface at <http://vespa.obspm.fr>.

The SOIR spectra at PSA level 2 (CODMAC - edited) and PSA level 3 (CODMAC - calibrated data) are already accessible through ESA's Planetary Science Archive repository in PDS3 format (<http://www.cosmos.esa.int/web/psa/venus-express>). Note that, in a near future, ESA will allow the accessibility of these data through the VESPA infrastructure (See McFarlane et al., this issue).

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 (usually 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 calibration dedicated measurement referred to as 2850.3.

SOIR spectral resolution was good enough to resolve the rovibrational absorption structure of the vibrational bands (Mahieux et al., 2015 [8]). When the density of the species was derived using concurrently absorption bands of several isotopologues (in the present case, only for CO₂, CO and SO₂, see for example Mahieux et al [5] and Vandaele et al, 2015 [6] and 2016 [9]), 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 [17]: 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 [17]. These isotopic ratios have not been corrected for Venus except for HDO. Bertaux et al. (2007) [18] mentioned a variable isotopic ratio with respect to the altitude. We used the mean isotopic ratio profile of HDO/H₂O described in *HDO/H₂O in the Venus Mesosphere and lower Thermosphere: Observations by SOIR/Vex*, Chamberlain et al. (2016, in preparation).

Hence, the name of the species in the files can thus be *CO2_0*, *CO_0*, *H2O_1* (for H₂O, excluding HDO), *H2O_4* (for HDO), *HCL_1* (for H³⁵Cl), *HCL_2* (for H³⁷Cl), *HF_1*, *SO2_1* or *AERO* (for aerosols).

It should be noted that the window used for the moving average introduced in section 1 was ten times smaller in the case of CO to avoid smoothing out real structures present in the profiles (see Vandaele et al. (2016) [6]). Remember also that the scale heights are different for each species as they are dependant of the molar mass. Two different profiles corresponding to two different smoothing factors used for the weighted linear moving average will be given, one corresponding to the default value (2) and the other to the minimum value as in Vandaele et al. (2016) [6].

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 [19] 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 in ppb for two 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.

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.

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.

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 the measurements all around Venus can be plotted using the “sky plotting window” as shown on Figure 1. 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.

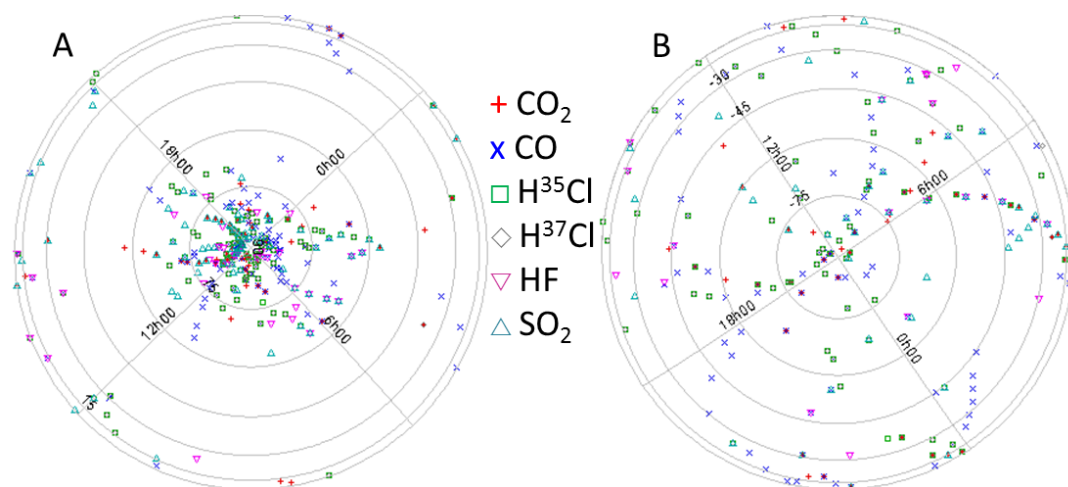


Figure 1: Positions on Venus of all the measurements. Panel A is the north atmosphere and panel B is the south atmosphere.

Other graphs using the metadata can be plotted to show information about the orbit of VEx. Figure 2 shows all measurements made by SOIR with respect to the distance to the Venus terminator and the solar longitude of Venus. It has been made using a “pair position plot” from the “plane plotting window” to see the extension of each measurement from its beginning to its end. During a measurement, the distance to the terminator of Venus is varying more when SOIR was closer to Venus. Due to the definition of the orbit of VEx, no measurement was made when Venus was between 100° and 180° of solar longitude.

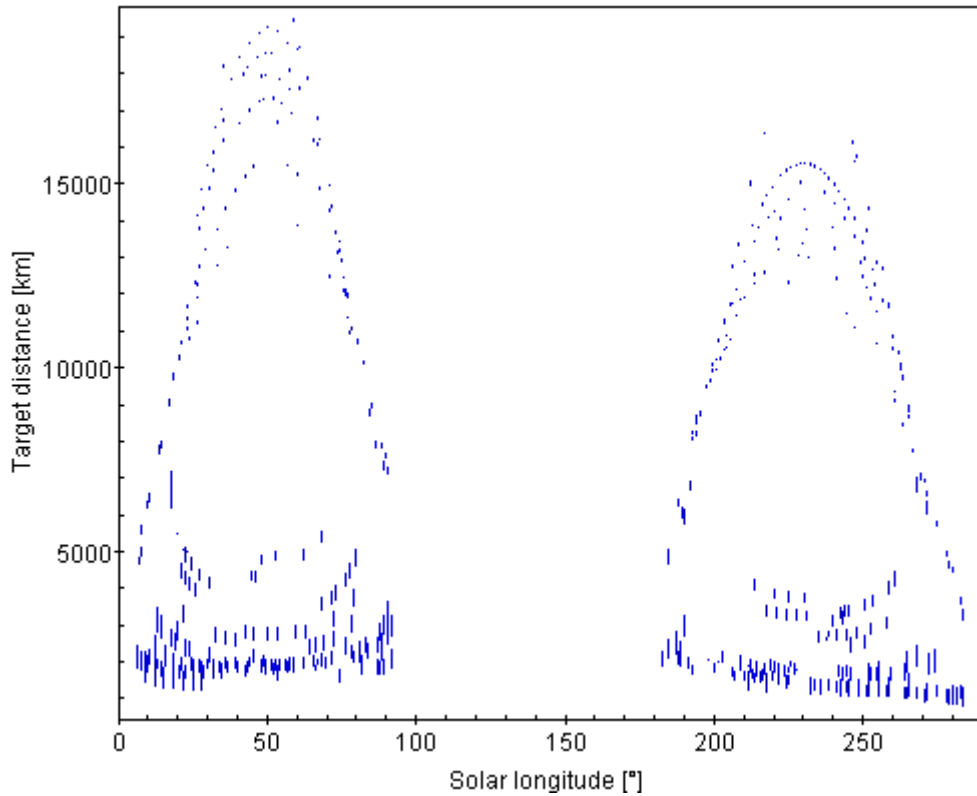


Figure 2 : Graph of all measurements made by SOIR following the solar longitude of Venus and the distance separating SOIR to the terminator of Venus.

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.

Figure 3 shows a plot of the CO₂ number density with respect to the altitude for all measurements made between 0° and 60° of latitude North. This plot contains some of the data displayed in Fig.3A from the paper of Mahieux et al. (2015c) [3].

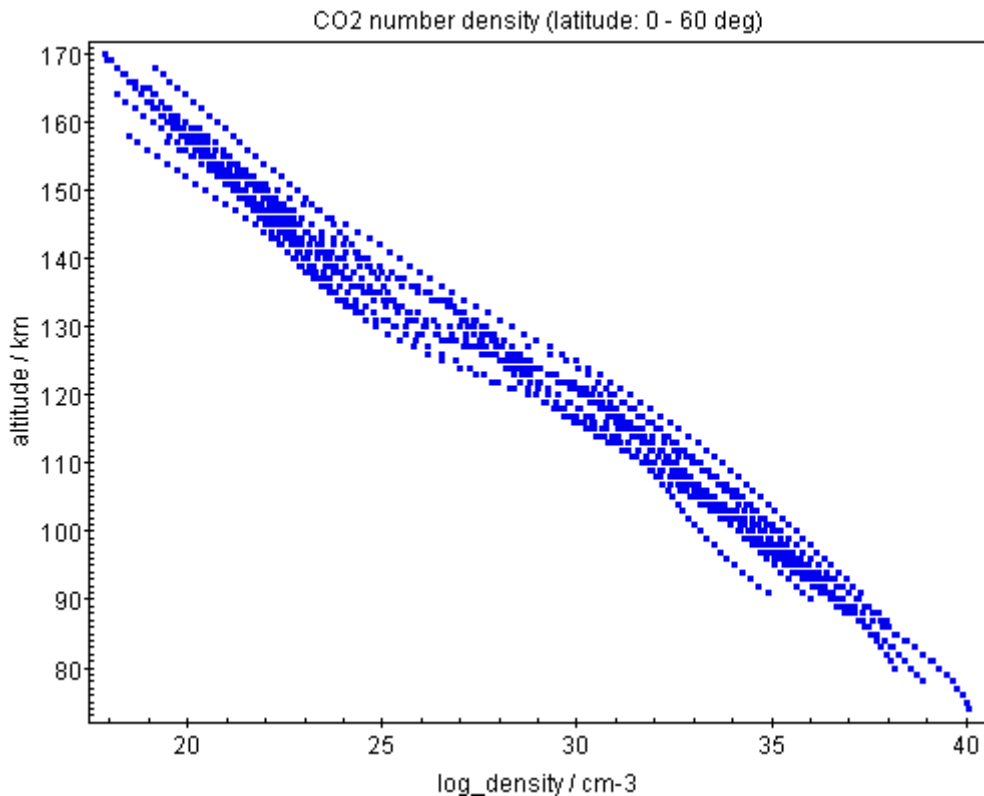


Figure 3 : CO₂ number density profiles of all measurements where CO₂ has been retrieved and located between 0 and 60 degree of latitude (Northern hemisphere).

5. Upcoming

The profiles for H₂O, 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 the SOIR solar transmittances has been developed and applied to all observations performed by the instrument during the complete duration of the mission [20]. These data (CODMAC level 2 and 3) 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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References

1. Nevejans, D., et al., *Compact high-resolution space-borne echelle grating spectrometer with AOTF based on order sorting for the infrared domain from 2.2 to 4.3 micrometer*. Applied Optics, 2006. **45**(21): p. 5191-5206.
2. Titov, D.V., et al., *Venus Express: Scientific Goals, Instrumentation and Scenario of the Mission*. Cosmic Res., 2006. **44**(4): p. 334-348.
3. Mahieux, A., et al., *Update of the Venus density and temperature profiles at high altitude measured by SOIR on board Venus Express*. Planet. Space Sci., 2015. **113-114**: p. 309-320.
4. Mahieux, A., et al., *Densities and temperatures in the Venus mesosphere and lower thermosphere retrieved from SOIR onboard Venus Express: Retrieval technique*. J. Geophys. Res., 2010. **115**(E12014): p. 10.1029/2010JE003589.
5. Mahieux, A., et al., *Densities and temperatures in the Venus mesosphere and lower thermosphere retrieved from SOIR on board Venus Express: Carbon dioxide measurements at the Venus terminator*. J. Geophys. Res., 2012. **117**(E07001): p. doi:10.1029/2012JE004058.
6. Vandaele, A.C., et al., *Carbon monoxide short term variability observed on Venus with SOIR/VEX*. Planet. Space Sci., 2015. **113-114**: p. 237-255.
7. Rodgers, C.D., *Inverse methods for atmospheric sounding: Theory and practice*. World Scientific, ed. N.J. Hackensack. 2000: University of Oxford.
8. Mahieux, A., et al., *Rotational temperatures of Venus upper atmosphere as measured by SOIR on board Venus Express*. Planet. Space Sci., 2015. **113-114**: p. 347-358.
9. Vandaele, A.C., et al., *Carbon monoxide observed in Venus' atmosphere with SOIR/VEX*. Icarus, 2016. **272**: p. 48-59.
10. Mahieux, A., et al., *Hydrogen Halides measurements in the Venus upper atmosphere retrieved from SOIR on board Venus Express*. Planet. Space Sci., 2015. **113-114**: p. 264-274.
11. Mahieux, A., et al., *Venus mesospheric sulfur dioxide measurement retrieved from SOIR on board Venus Express*. Planet. Space Sci., 2015. **113-114**: p. 193-204.
12. Fedorova, A., et al., *HDO and H₂O vertical distributions and isotopic ratio in the Venus mesosphere by Solar Occultation at Infrared spectrometer onboard Venus Express*. J. Geophys. Res. 2008. **113**(E00B22): p. doi:10.1029/2008JE003146.
13. Wilquet, V., et al., *Preliminary characterization of the upper haze by SPICAV/SOIR solar occultation in UV to mid-IR onboard Venus Express*. J. Geophys. Res., 2009. **114**: p. E00B42.
14. Wilquet, V., et al., *Optical extinction due to aerosols in the upper haze of Venus: Four years of SOIR/VEX observations from 2006 to 2010*. Icarus, 2012. **217**(2): p. 875-881.
15. Vandaele, A.C., et al., *Contribution from SOIR/VEX to the updated Venus International Reference Atmosphere (VIRA)*. Adv. Space Res., 2015. **in press**.
16. Erard, S., et al., *Planetary Science Virtual Observatory architecture*. Astronomy and Computing, 2014. **7-8**(Special Issue on The Virtual Observatory: I): p. 71-80.
17. Rothman, L.S., et al., *The HITRAN2012 molecular spectroscopic database*. J. Quant. Spectrosc. Radiat. Transfer, 2013. **130**: p. 4.
18. Bertaux, J.L., et al., *A warm layer in Venus' cryosphere and high altitude measurements of HF, HCl, H₂O and HDO*. Nature, 2007. **450**(29 November): p. 646-649, doi:10.1038/nature05974.
19. Taylor, M.B., *TOPCAT & STIL: Starlink Table/VOTable Processing Software*. ASP Conference Series, 2005. **347**: p. 5.
20. Trompet, L., et al., *Improved algorithm for the transmittance estimation of the spectra obtained with SOIR/Venus Express* Applied Optics, 2016. **55**(32): p. 9275-9281.