European Unified Research on Observations of Venus using co-ordinated Space- and Earth-based facilities

**Reporting**

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### Project Information

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<td>Grant agreement ID: 606798</td>
<td>FP7-SPACE</td>
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### Final Report Summary - EUROVENUS (European Unified Research on Observations of Venus using co-ordinated Space- and Earth-based facilities)

**Executive Summary:**

Venus is Earth’s closest sibling, but it has ended up with a radically different climate. The main intention of the EuroVenus project has been to understand what makes Earth and Venus different today. In visible wavelengths the Venus disk appears covered by thick sulfuric acid clouds. Our multi-disciplinary approach is to study the atmosphere by explaining atmospheric composition and minor species chemistry, understanding the global dynamics/wind system, and how they relate to each other. Like climate studies on Earth, The EuroVenus project has relied on long series of inter-calibrated measurements, in order to (1)
enhance the legacy of ESA’s Venus Express mission data through cross-validation of complementary ground-based telescopic observations; (2) position European ground-based researchers in a worldwide leadership on Venus research, after the end of the Venus Express mission; (3) strengthen the position and visibility of European researchers in the emerging field of comparative planetology. The Venus Express instruments and ground-based observations have considerably increased our knowledge of the Venus atmospheric thermal structure above ~40 km and provided new information above 100 km. Our project has set up new bases for a global Venus climatology, continuing the progress accomplished over European Space Agency’s Venus Express mission (2006-2015), and preparing for future Venus exploration. The main results of the project are an enhanced climatology of the Venus atmosphere, and the delivery of high level data products to the planetary science community worldwide.

One of the major goals of the Venus Express (VEx) mission has focused upon increasing our understanding of the highly variable global circulation and wave processes impacting the Venus mesosphere-thermosphere (~80 – 200 km). Several VEx instruments (e.g. SOIR, SPICAV and VIRTIS) and ground based observations have provided measurements that characterize the upper atmosphere structure, trace gases chemistry and underlying variable dynamics. As an example, a EuroVenus team led by P. Machado has evidenced the meridional wind circulation at cloud-top in both dayside hemispheres (Machado et al. 2016). Considerable variability in the temperatures and densities is seen above 100 km but certain features appear to be systematically present, such as a succession of warm and cool layers. This large ensemble of results have been presented in several international conferences. Each partner beneficiary has prepared an archive of high-end products available in their home institute on a proprietary server, and prepared an agreed query/format documentation to make them accessible from the main project website.

The website for the EuroVenus project http://www.eurovenus.eu also presents the teams’ science activities, results from the consortium and news and updates on present as well as future projects for the spatial exploration and study of planet Venus, our nearest neighbour. The site includes links to partner Institutes and European teams, a presentation of reasons to explore and study Venus, and links / outreach material for dissemination toward a larger public. Higher-level data archive, the nature of our data products, search interface when applicable, server location and co-authorship policy is publicly accessible through the project website, allowing the results to be available to the wider scientific community. The outreach media produced during the EuroVenus project went beyond the basic requirements of conveying information about the consortium’s activities; they also are visually attractive and appealing for a wider public than normally targeted by such films, ensuring that the benefits of the EU funding will be felt well beyond the end of the funded period.

Project Context and Objectives:

CONTEXT AND MAIN OBJECTIVES

The goal of the EuroVenus project has been to investigate in detail the dynamics and composition of the middle and lower atmosphere of Venus by combining data from Venus Express instruments (VIRTIS, VMC) with simultaneous data acquired from several ground-based telescope facilities. Venus Express observations, with for example the SOIR and VIRTIS instruments, cover both Southern and Northern hemispheres. They have delivered critical information on the dynamics of the Venus atmosphere, such as wind speed, or temperature field measurements. For instance, the SOIR instrument provides
measurements of the total density and the temperature in the mesosphere and lower thermosphere which can readily be compared with ground-based observations, in a region where dynamical processes change rapidly with altitude. Based on the exploitation of past Venus Express measurements, the project has also successfully performed coordinated observations of Venus using different techniques, to provide a detailed analysis of dynamical and chemical couplings between different levels of the atmosphere that are probed simultaneously by different instruments.

C1 - Mechanisms of Venus circulation

Despite recent progress in modelling and new observations, mechanisms controlling the global circulation still remain largely unknown, and underconstrained by data. The circulation up to the cloud tops is characterised by an increasing zonal wind, starting from an altitude of 10 km. The zonal superrotation of the cloud tops, which circle the planet in only 4.4 days, contrasts with the long rotation period of the solid globe (243 terrestrial days). At this altitude the latitudinal profile of the zonal wind is variable and is coupled with the solar tide. It is uniform at low latitudes, dropping poleward from mid-latitudes, where an intense meridional wind shear develops. On the retrograde zonal superrotating flow itself, at the basis of the mesosphere, two main, large-scale, variable components are superimposed: a solar tide and a traveling four-day wave. The solar tides are global-scale motions forced by solar heating. They are stationary with respect to the sub-solar point and thus move upstream relative to the fluid. The four-day wave consists of a Y-shaped feature seen in UV images which has been identified as a Kelvin wave. The forcing and dissipation mechanisms of the four-day wave and the solar tide are major phenomena that certainly play a role in the global dynamics but are as yet poorly understood. Other important features of the Venus atmosphere are the two polar vortices, observed to be accompanied by a surrounding collar of colder air, and the recently discovered large stationary wave associated with mountain topography, discovered by the Akatsuki probe (Fukuhara et al. 2017).

Venus’ middle atmosphere (65-120 km, also known as the mesosphere) is a transition region between the zonal retrograde circulation of the lower atmosphere (up to 65 km) and the sub-solar to antisolar (SSAS) flow of the upper thermosphere (above 120 km). Thermal profiles and winds in the mesosphere have revealed that these two types of circulation coexist, with winds varying by tens of metres per second over both long (yearly) and short (weekly or daily) timescales. Once the measurements of wind components with different techniques are validated, it is possible to construct further quantities to diagnose the circulation, such as meridional and momentum fluxes, or potential vorticity. The accumulation of wind and temperature measurements over the duration of the Venus Express mission has already provided a wealth of data (a large fraction of which have been analysed by the EuroVenus teams. This represents a robust diagnostic of the latitudinal exchanges of heat and momentum at the cloud tops, and it will also be used to benchmark and optimize the Venus Global Circulation Models (GCMs) under development.

C2 - Doppler velocimetry in the visible range

The main purpose of ground-based Doppler velocimetry is to provide direct wind velocity measurements using visible Fraunhofer lines scattered by Venus’ cloud tops. Wind speeds are measured using Doppler-shifted spectroscopy, providing signal-to-noise limited precision of ~5 m/s. The ground-based telescopes acquire data in several wavelength ranges (millimeter wave, visible, IR), and utilize several tracers: CO
and isotopic 13CO rotational lines in the millimeter wave range, sampling the 105 km and 95 km regions respectively; solar Fraunhofer and CO2 lines in the visible (dayside), sounding cloud tops (70 km) and a few kilometers above (Widemann et al., 2007, 2008; Machado et al., 2012, 2014, 2017). In each observation, several target points are observed on the Venus disk, and line-of-sight projected velocities are measured. Given the time-variable character of the mesospheric dynamics, we will try, as much as possible, to obtain coordinated observations from several telescopes, in order to infer a vertical picture of the dynamical regime of Venus’ mesosphere at a given epoch and to investigate the couplings between the different levels that will be probed simultaneously by the Venus-Express payload instruments.

C3 - Cloud tracking from orbit

Cloud tracking in images taken at different wavelengths has proved an invaluable tool for extracting wind speeds at distinct vertical levels in the cloud region. In Venus express, two cameras can be used for measuring winds by cloud tracking: VIRTIS-M, a visual spectrometer capable of taking a sequence of images at multiple wavelengths. The visible channel is typically used for dayside observations, and the infrared channel is sensitive to the thermal radiation from the nightside; The Venus Monitoring Camera (VMC) is a wide-angle, multi-channel CCD, designed for global imaging and operating in the visible, ultraviolet, and near infrared ranges.

C4 - Submillimeter and millimeter wave observations

Observing Venus at millimeter and submillimeter wavelengths with heterodyne spectroscopy provides us with a complementary means to probe the upper mesosphere of Venus. Lines of minor species are formed at altitudes ranging from 70 km to 110 km, depending upon the strength of the transition used. Heterodyne spectroscopy measurements have been performed with single dish antennas for decades in the millimeter range for CO, HDO and H2O (Encrenaz et al. A&A 246, L63, 1991; Icarus 117, 162, 1995), and more recently in the submillimeter range for CO, SO2 and SO (Sandor and Clancy, Icarus 208, 49, 2010). These observations have shown a significant increase of the SO2 mixing ratio above 90 km, which seems to indicate that a source of sulfur is present at high altitude. The absence of detection of H2SO4 suggests that this source might come from a sulfur-bearing aerosol. The submillimeter observations also discovered a very strong temporal variability in the SO2 and SO abundances, on timescales of the range of a few days in the case of SO. The behaviour of sulfur in the mesosphere of Venus is still far from being understood and requires long-term monitoring. In addition, the high spectral resolution of these observations (less than 100 kHz) allows determining the thermal structure and the wind fields at altitudes ranging from 70 km to 110 km.

C5 - Mapping CO2, H2O and SO2 in the 7-8 μm range

Sulfur dioxide has transitions in the thermal infrared which can be observed from the ground between the CH4 and H2O terrestrial absorption bands. It is thus possible to complement the space observations of Venus Express by using a thermal infrared mapping spectrometer with high spatial and spectral resolution. Our team has proposed to use this method to map H2O and SO2 in the mesosphere of Venus. Its main advantage is that the simultaneous observations of weak transitions of CO2 and SO2 allow deriving a mixing ratio which, to first order, is independent of geometrical conditions (airmass) or atmospheric
parameters (temperature profile, altitude level of the cloud deck). It is especially interesting in the case of Venus because the altitude of the upper cloud is expected to show strong variations over the disk, especially between the dayside and the night side. These differences translate in a strong variation of the intensities of the CO2 and SO2 lines but, as long as these transitions remain weak (with a depth less than 10 percent), their mixing ratio will give us an estimate of the SO2 mixing ratio.

C6 - The neutral atmosphere using radio science experiment

The VEx Radio Science Experiment (VeRa) uses the radio subsystem of the spacecraft to study the structure and dynamics of the ionosphere (90 – 600 km) and the neutral atmosphere (40 km – 90 km) at two coherently related radio frequencies of 8.4 GHz (X-band) and 2.3 GHz (S-band). A detailed experiment description is provided by Häusler et al. (2006, 2007). Radio occultation observations by the VeRa experiment provide the temperature structure at a vertical resolution of a few hundred metres revealing in detail gravity wave patterns, the distribution of the static stability parameter, and the occurrence of planetary wave structures.

Due to the highly elliptical orbit of the VEX spacecraft, the data base provides good spatial coverage in the southern hemisphere and a more clustered distribution poleward of 65° in the northern hemisphere. The retrieved profiles of temperature, pressure and density are almost equally distributed between the day side (6 – 18 hours LT) and the nightside (18 hours – 6 hours LT). Currently the VeRa data base consists of more than 600 profiles of temperature, pressure and neutral number density.

The temperature profiles from the two VEx instruments SOIR and VeRa have an overlap of about 20 km in the altitude range 70 km – 90 km. It is therefore of great interest to combine temperature profiles from both experiments, which is one of the purposes of the EuroVenus project. The fine resolution and the wide coverage of the VeRa data is essential to resolve atmospheric wave features, to better understand the poorly-constrained energy and momentum budget. Radio sounding of the sub-cloud region leads to a strong absorption of radio signals. Sulfuric acid vapor is the most opaque constituent in Venus’ atmosphere at radio wavelengths. The received signal intensity is used to derive radio absorptivity profiles. The variable distribution of the trace gas H2SO4 with planetary latitude can be taken as evidence for atmospheric dynamics. Absorptivity profiles are therefore a valuable tool for revealing atmospheric dynamics (Oschlisniok et al., 2012).

C7 - Temperature and CO2 density using solar occultations

The terminator in the Venus mesosphere and thermosphere is a region of additional interest as a transition between the hot dayside and the cold nightside. However, it is poorly understood, since only a few measurements were obtained at these particular local solar times, i.e. 6:00 A.M. and 6:00 P.M. The SOIR instrument on board Venus Express offers the possibility to routinely detect and monitor the density of various key Venus species, such as H2O, CO, HCl or SO2 trace gases. The SOIR instrument is particularly well suited to help identify the dynamic and chemical processes that take place at the terminator as it also measures CO2 absorption, the main constituent of the Venus atmosphere, across a broad spectral window. The observed atmospheric transmittance spectra are subsequently inverted to obtain vertical density profiles, extending from 70 km up to 170 km, from which temperature profiles are
derived applying the hydrostatic equilibrium condition (Mahieux et al. 2012). Based on a subset of 59 SOIR observations, an atmospheric model, called VAST (Venus Atmosphere from SOIR measurements at the Terminator) has recently been built and revealed the persistent presence of a striking cold layer at an altitude of 125 km that was never observed before, and two warm layers below it (~110 km) and above it (~145 km).

All in all, temperatures derived with SOIR compare well with data available in the literature at low altitudes, in the 1 mbar to 10-2 mbar region (~85 to 100 km). The agreement is also reasonable up to 10-5 mbar at low latitudes when compared to SPICAV measurements (VEX mission, Bertaux et al., 2007b) on the nightside and is almost perfect down to 102 mbar (~70 km) at high latitudes when compared to VeRA measurements (VEX mission, Tellmann et al., 2009; Piccialli et al., 2012). There remain however discrepancies with other results from missions to Venus or from ground-based measurements and these are not yet explained or understood, in addition to the lack of data above 130 km of altitude.

C8 - The transit of Venus of 2012

With the 6 June 2012 transit of Venus completing the pair of rare events that began on 8 June 2004, we successfully obtained a wide-ranging series of observations to gather as much 21st-century data as possible. During a solar transit, close to ingress and egress phases, the fraction of Venus disk projected outside the solar photosphere appears outlined by an irregular thin arc of light called the “aureole”. We have shown that the deviation due to refraction and the aureole intensity are related to the local density scale height and the altitude of the refraction layer above the opaque upper haze layers (Tanga et al. 2012). Since the aureole brightness is the quantity that can be measured during the transit, an appropriate model allows us to determine the scale height H and the half-occultation radius relative to slanted opacity τ~1 best reproducing the observations. In general, different portions of the arc can yield different values of these parameters, thus providing a useful insight of the physical properties variations of the Venus atmosphere as a function of latitude. The results obtained on 8 June 2004 and June 5-6, 2012 thus depend strongly upon transmittance and of extinction profiles obtained by Venus Express’ SOIR instrument.

Project Results:
MAIN SCIENCE & TECHNOLOGY RESULTS/FOREGROUNDS

As we described in the Executive summary and the Summary description of the project, intention of the EuroVenus consortium is to understand what makes Earth and Venus so different today. One key approach is to study the atmosphere by (1) explaining atmospheric composition and minor species chemistry and (2) understanding the global dynamics/wind system. Those two main approaches jointly relied on (1) observations from Venus Express and (2) observations with ground-based instruments, studied in coordination between all EuroVenus beneficiaries. Like climate studies on Earth, The EuroVenus project relies on exploitation of long series of inter-calibrated measurements. Over the course of ESA Venus Express mission, in orbit around Venus between April 2006 and January 2015, ground-based coordinated observations were organized with the following specific objectives:

- perform measurements not feasible by Venus Express,
- obtain cross-validation of measurements by different techniques and record different diagnostics of similar phenomena,
- obtain simultaneous measurements sampling a large range of altitudes and
- improve the temporal baseline on time-varying phenomena.

The EuroVenus project has expanded this strategy over a three-year period (October 2014 – September 2016). It has been composed of three main research themes, oriented towards 1. the exploitation of the large Venus Express dataset; 2. the acquisition and analysis of new ground-based observations of cloud motions and Doppler shifts in the cloud layer and above; and, finally, 3. the characterization of trace species distributions below the cloud layer. Dr. T. Widemann led the Support Investigation of ground-based observations in support of ESA Venus Express mission. This coordination has taken the form of maintaining a website for exchange of information among the teams, convening of dedicated sessions in conferences, and providing ESA support to telescope proposals. Dr. C. Wilson has led the coordination of EuroVenus observers from the point of view of ESA Venus Express space-based operations and planning. This involved until the end of 2014 the collection of requests for coordinated spacecraft observations from ground-based observers and the implementation, as far as possible, of these requests into the spacecraft observations plan. Through this coordination intended to advance an integrated approach based on the exploitation of the Venus Express dataset.

The project has therefore enhanced the legacy of ESA’s Venus Express mission data through cross-validation of complementary ground-based telescopic observations; it has also positioned European ground-based researchers in a worldwide leadership on Venus research, after the end of the Venus Express mission; and thirdly, it has strengthened the position and visibility of European researchers in the emerging field of comparative planetology. The Venus Express instruments and ground-based observations have considerably increased our knowledge of the Venus atmospheric thermal structure above ~40 km and provided new information above 100 km. Our project has set up new bases for a global Venus climatology, continuing the progress accomplished over European Space Agency’s Venus Express mission (2006-2015), and preparing for future Venus exploration. The main S/T results of the project are an enhanced climatology of the Venus atmosphere, and the delivery of high level data products to the planetary science community worldwide, as developed below.

S1 - Coordinated observations of ESA Venus Express and the ground-based community

European Space Agency’s Venus Express successfully conducted science observations at Venus for almost a decade, before exhausting its propellant and burning up in Venus atmosphere in January 2015. The end of ESA/Venus Express mission did not affect our initial plans for ground-based observations during first and second semester 2015 and first semester 2016 regarding Reporting Period 3 (Widemann et al. : Feb. & April 2015, Jan. 2016 ; Encrenaz et al.: March 2015 and January 2016 ; Krauze et al. : Oct. 2015). In addition, experience gained throughout the two first years of the consortium made coordination easier. The January 2016 missions were extremely successful due to satisfactory weather conditions. Preliminary results could be presented at the Oxford conference in the framework of task T6.1 [P. Machado et al, Ground and space based cloud-top wind velocities using CFHT/ESPaDOnS (Doppler velocimetry) and VEx/VIRTIS (cloud tracking) coordinated measurements] and task T4.1 [T. Encrenaz et al., Variability of SO2 and HDO and thermal structure in the lower mesosphere of Venus from infrared spectroscopy, International Venus Conference 2016, Oxford, UK, 4-8 April 2016]. So was the task T5.1 THIS IR heterodyne mission at Kitt Peak in Oct. 2015 [Krauze et al., Temperature Measurements in Venus
Upper Atmosphere between 2007 and 2015 from ground-based Infrared Heterodyne Spectroscopy]. In addition, the simultaneous observing periods of Jan. 2016 at CFHT and IRTF on top of Maunakea have been an excellent outreach opportunity for the filming of EuroVenus Episode #2 in facilities for Venus observations (http://eurovenus.eu/News/64/ cf. deliverable D3.3).

The scientific impact of the end of the Venus Express mission in Dec. 2014 has been minimized by the exploitation of redundancy between ground-based instruments, and between VEx instruments, and their previous intercomparison, as described in the DoW part B p. 56 subsection 1.3.5 (Significant risks, and associated contingency plans). Furthermore, operations of Akatsuki, or Venus Climate Orbiter, since its second attempted orbital insertion in Dec. 2015, are in regular science operations since April, 2016. JAXA will gradually adjust the orbit for shifting its elliptical orbit to the period of about nine days. Its instruments (most notably IR1/2, UVI and LIR) are expected to provide results this year and the coming years. Further collaborations between our teams and the Japanese teams were expected to (1) help define new strategies for coordinated observations, (2) ensure that the benefits of the EU funding will be felt beyond the end of the funded period. A poster presentation at the Oxford Conference in April 2016 explained this multi-year effort in the framework of T2.1 [Widemann, T. et al., International ground-based support to Venus Express and Akatsuki missions, 2007-2017]. Akatsuki LIR camera will observe nightside cloud-top temperature to map of global cloud-top temperature, if one assumes that the large-scale structures (e.g. associated with Y-feature) lasts this long, they will be eventually compared to any spatial structures seen in IRTF/TeXes retrieved parameters (temperature structure, SO2, HDO retrievals), and with wind field retrievals. If wind tracking from LIR data are also available, this can also be compared with dayside wind retrievals such as those obtained with CFHT/ESPaDOnS (WP6), the VeRa results (WP5) and the SPICAV SOIR results (WP7, T7.1). A Venus & SOIR Workshop took place at University of Rikkyo, Tokyo, 26-28 Sept. 2016 to support training on exploitation of SOIR data by the Japanese community and coordinated support campaign for Akatsuki. (cf. deliverable D2.5). Akatsuki IR2 will observe middle/lower cloud winds through feature tracking. In principle, one could look for correlations between mean cloud opacity (as measured by mean brightness at 1.735 or 2.26 um channels) and mesospheric SO2 and/or HDO levels observed using various techniques from the ground (IRTF, sub-mm and mm wave).

In general, coordinated observations have improved the latitudinal coverage and temporal baseline, while allowing cross-validation of measurements by different techniques. Looking beyond the end of EuroVenus in October 2016, HST will potentially observe near maximum elongations in Dec 2016-Feb 1 2017 and May 21-June 21 2017, while another round of proposal requests for observing Venus have been submitted to major ground-based facilities time allocation committees for 2017 (ALMA, JCMT, CFHT, IRTF, AAT, APO), ensuring the pursuit of the work supported by the European Commission well beyond the funded period.

S2 - Comparison and cross-validation of results from different RTD work packages

Venus’ mesosphere (60 – 120 km altitude) exhibits complex photochemistry cycles and dynamical processes that are still poorly understood. A strong variability, both on day-to-day as well as longer timescales, affects the thermal structure of this atmospheric region, especially near the morning and evening terminators, where large density and temperature variations were observed (Clancy et al. 2012; Mahieux et al. 2015; Piccialli et al. 2015). Sulfur dioxide and water vapor are key species in the
photochemical cycles taking place in the troposphere and mesosphere of Venus (Mills et al. 2007; Zhang et al. 2012). Both molecules are abundant in the lower troposphere (150 ppm and 30 ppm respectively – after Marcq et al. 2008, Bézard et al. 2009). They are carried by convective transport, together with the Hadley circulation, up to about 60 km where SO2 is photodissociated and combines with oxygen atoms to form SO3. SO3 reacts with H2O to form H2SO4 which condenses in the clouds enshrouding the planet. Above the clouds, both SO2 and H2O are depleted down to about 0.1 – 1 ppm and 1 – 2 ppm respectively. Observations in the UV and in the IR, using Venus Express and ground-based high-resolution imaging spectroscopy have shown evidence for strong temporal variations of the SO2 abundance on a timescale as short as a couple of hours, which are not well understood presently. Millimeter (mm) and submillimeter (submm) heterodyne spectroscopy offers the opportunity of probing the mesosphere of Venus by monitoring minor species and winds. HDO and H2O have been observed in the upper mesosphere (about 95 km) at mm and submm wavelengths respectively. Sandor et al. (2012) detected SO and SO2 in the upper mesosphere of Venus (about 90 km) by using submm observations at the James Clerk Maxwell Telescope (JCMT). Surprisingly, their abundances were found to be significantly larger than in the lower mesosphere, implying the presence of an extra source of sulfur, possibly in the form of sulfur aerosols (Sander et al. 2012). They also exhibited strong temporal variations, with SO being much more depleted on the night side, consistent with the hypothesis that SO is a photodissociation product of SO2.

S3 - Cross-calibration of variable winds

On Venus the atmosphere at cloud top level spins some 60 times faster than the solid globe. This superrotation (also observed on Saturn’s moon Titan, albeit with only a factor of 15 between the rotation of the globe and the high atmosphere), in contrast with the terrestrial climate system, is a long-standing question in Solar System atmospheric studies. In atmospheres receiving a surplus of energy at equatorial latitudes, upward and poleward transport of angular momentum by the Hadley cell generates high-speed jets at high latitudes in the upper atmosphere. Ground based telescopes have the advantage that they can be equipped sophisticated spectrometers far too massive and complex to deploy on a spacecraft; these ground-based instruments can thus be sensitive to trace constituents or faint motions of the atmosphere in a way which is complimentary to spacecraft observations. Earth-based telescopes have enough spectral sensitivity that they can directly measure the actual velocity of cloud particles by measuring the Doppler shift of sunlight they reflect. Co-ordinated campaigns of observations with Venus Express confirmed that the velocities of individual cloud particles did indeed match up very accurately with the velocities calculated from cloud imagery. This provided a vital confirmation that decades of cloud tracking observations, dating back to the 1970s, were indeed representative of true atmospheric circulation.

In April 2014, a CFHT run was allocated to our group in the framework of the EuroVenus project. VEx orbit planning indicated that VIRTIS and VMC instruments would be on during (1) orbit 2918 at: Apr. 16 and (2) orbit 2923 at Apr. 21, for VIRTIS-M; VMC camera from orbit 2918 (16 Apr) till orbit 2923 (21 Apr.). Eventually, only orbit 2918 was used for simultaneous VIRTIS-M UV cloud tracking at cloud tops with ground-based Doppler winds. The observations took place April 16th to 19th 2014. Venus was observed at a phase angle Φ (Sun-Target-Observer) of 76.4 ± 0.7°, with surface brightness at 1.34 mag/arcsec, apparent magnitude -4.2 and an angular diameter of ~18.7 arcsec. Due to operational constraints, allocated periods were slightly different from day to day: Apr. 16, 09:00-11:00 HST (19:00-21:00 UTC);
Apr. 17 and Apr. 18, 07:00-11:00 HST (17:00-21:00 UTC) \( \rightarrow \) Apr. 19, 07:00- 10:30 HST (17:00-20:30 UTC). The observing strategy has been to displace the entrance fiber of the spectrograph along points on the dayside hemisphere. Simultaneously, two Venus Express orbits were selected (VV2918 on April 16; VV2923 on April 21). Cloud-tracking analysis was performed in the UV wavelength of 380 nm. The separation between image pairs used to track the cloud features motions (1 h in most cases) as well as the associated error in individual cloud features were similar to the mean standard deviations of the global wind profiles (10 m/s). A total of seven pairs of images were analyzed, four of them exactly simultaneous with our ground-based measurements (VV2918), the three last pairs occurring Apr. 21, two days after the last day of CFHT/ESPaDOnS measurements on Apr. 19 but interestingly, co-located in the same latitudinal and local time range for temporal variation assessment with one period of zonal superrotation. We were also able to match the cloud-tracking features to the only region where ground-based Doppler velocimetry constrains unambiguously the meridional wind component (HPA meridian) near 38 deg longitude or 9-10 am local time. The day-averaged zonal wind reflects the stability of the regime at constant solar-fixed coordinates. This is in agreement with previous observations combining several years of observations by VIRTIS-M (Hueso et al., 2015), indicating higher zonal speeds near the morning terminator. In some occurrences, in particular, we detect a zonal wind increase of about 20–30 m s⁻¹ near morning terminator, beyond the confidence level of 2-σ, at the equator and 30°N.

Constraining the meridional wind component at cloud top has long-time been an open issue for diagnosing the maintenance of the super-rotation of the Venus atmosphere by determining the global mean and eddy circulations, as well as the accompanying meridional transports of angular momentum and energy (Limaye and Rengel, 2013). The role of thermal tides that transport angular momentum vertically in the low latitudes was confirmed by recent works (Lebonnois et al., 2010; Takagi and Matsuda, 2007). We also note that the latitudinal distribution of zonal wind at cloud tops may result from an equilibrium between the impact of thermal tides, and the angular momentum transport by the meridional circulation (Lebonnois et al., 2010), providing grounds for future systematic, simultaneous observations of both dynamical regimes (Machado et al. 2014, 2017).

S4 - Temperature @ 10μm in CO2 non-LTE heterodyne and IRTF – TEXES

TEXES data have been obtained for both the evening terminator (Jan. 2012 & Mar. 2015) and the morning terminator (Oct. 2012, Feb. & Jul. 2014). Measuring CO2 transitions of various intensities in different bands at 7, 10.5 12.5 and 19 μm allows us to retrieve information about the thermal structure above the clouds as a function of latitude and local hour. At high latitudes (around 70 N and S), the data show the isothermal or inversion layer just above the cloud associated with the polar collar. This effect is clearly stronger around the morning terminator (Oct. 2012, Feb. & July 2014) than at the evening terminator (Jan. 2012, March 2015). In addition, data recorded in the CO2 hot band at 10.5 μm show at the limb a non-thermal emission on the dayside, consistent with previous heterodyne spectroscopy observations at the same wavelength.

The TEXES brightness temperature maps are globally homogeneous and isotropic, with no apparent variation between the day side and the night side. They show some intensity variations from an IRTF run to another, by as much as 20% in radiance at 7.4 μm, and 10% in radiance at 19 μm; part of these differences might be due to the instrumental uncertainty in measuring absolute radiances. When the
morning terminator is observed, the continuum maps show a drop at high latitude corresponding to the polar collar, also associated with a decrease of the temperature gradient over the penetration level. This effect, previously observed, has been interpreted as the signature of a diurnal cold wave at high latitude (Migliorini et al., 2012; Yamamoto and Takahashi 2012). This effect is absent, as observed in the 2012 TEXES observations and confirmed later, when the evening terminator is observed (January 2012, March 2015). It must be noticed, however, that this effect is clearly visible in 3 runs corresponding to the morning terminator (October 2012, February 2014, July 2014), but is significantly weaker on the last one (January 2016). When the morning terminator is observed, at latitudes above 60º, the temperature gradient upon the penetration level can be null or negative, which implies that the thermal profile becomes isothermal or shows an inversion. In this case, the retrieval of the SO2 and HDO mixing ratios is no more reliable (Encrenaz et al., 2016).

The mesospheric temperature structure at Venus’ dawn and dusk terminators can be observed by mid-infrared heterodyne (IR-het) spectroscopy sensitive to a pressure level of 1 μbar. This corresponds to an altitude of about 110 km ± 10 km. In total 74 observations from five observing campaigns, between 2009 and 2015 are available to study the thermal structure of the morning terminator side. Two campaigns are close to the superior solar conjunction, two at maximum western elongation and one took place close to the inferior solar conjunction. The two campaigns close to superior solar conjunction (June 2011 and March 2013) offer the opportunity to study both terminators simultaneously, though they have the disadvantage of a very low spatial resolution. The database of the evening terminator side contains 71 single observations from five campaigns. Two campaigns are close to superior solar conjunction (June 2011 and March 2013) and two are close to inferior solar conjunction (March 2009 and May 2012). One campaign took place during maximum eastern elongation (March 2012). The approximate spatial resolution is the same as for similar observing conditions at the morning terminator. The greatest number of measurements at the evening side of the terminator is in March 2013, with 26 single observations, within 30 minutes local time from the terminator. March 2012 has the fewest measurements with 8 single observations, obtained almost directly on the terminator. The same is true for the May 2012 campaign. Observations from June 2011 are the furthest from the terminator (16:30 hour local time, Krauze et al., 2017).

S5 - Optical extinction of aerosols (SOIR) and Venus transit aureole photometry (SDO/HMI)

The Venus aureole is a refracted, extremely flattened image of a portion of the solar photosphere, having the same surface brightness if the atmosphere is totally transparent. It is only observed during a transit. The thickness of the refracting layer, is unresolved in remote observations. Through WP8 we explored different approaches to model the variation of the aureole brightness, ranging from simple isothermal modeling to multi-layer. We implemented both direct (starting from an imposed vertical profile) and inverse modeling (iteratively determining the vertical profile). Our final model results provide at the same time the vertical density profile (from which temperature can be derived), the altitude of the absorbing clouds (optical thicknessτ=1) and the maximum altitude that we can probe with aureole. The maximum brightness of the aureole (around 10–1, normalized units) occurs at very low f values, i.e. at distances when the disk of Venus is almost entirely inside the solar limb. At this geometry the luminosity is dominated by Sun light crossing the atmosphere at the highest altitude probed by the aureole. The corresponding sunlight beams are affected by a very small (sub-arcsec) total deviation due to refraction. As the aureole image formed by
refraction preserves the surface brightness of the source (in case of a perfectly transparent atmosphere), our normalization implies that the thickness of the atmospheric layer contributing to the aureole is \( ~10^{-1} \) arcsec= 20 km. If additional opacity due to light scattering by aerosol particles above the cloud tops is included, the real altitude range can be higher.

The core of the computation we applied is the application of the refraction equation at all layers, providing the total refraction angle and the associated attenuation. From the refraction angle, a light ray is traced back from the observer toward the source, on a plane containing the observer, the center of Venus and the point of the terminator where refraction must be analyzed (at +49° in our case). If the ray falls on the solar photosphere, the corresponding flux contribution (weighted by \( \phi \)) is considered. The aerosol absorption factor is also used to model the transition between the transparent and the opaque atmosphere. By adding the contribution of each layer, the aureole theoretical brightness is obtained. The computation is then repeated for each \( f \) to reconstruct the full light curve, to be compared with SDO/HMI observations. The result of this procedure is shown in Fig. 3, where the green curve is the predicted flux obtained by the direct model, and the blue curve the SDO/HMI data. The fit is in remarkable agreement for \( f > 0.08 \) where the general slope is perfectly reproduced. The cloud altitude and the scale height of the aerosols are obtained iteratively by a least-squares minimization. The resulting values are \( r_\tau = 89.0 \text{ km} \) and \( r_\tau = 4.8 \text{ km} \), respectively. The various data sets we analyzed (ground-based, and from Earth-orbiting solar observatories, NASA/Solar Dynamics Observatory/HMI and JAXA/Hinode) have proven to be complementary to each other, in terms of time sampling, spatial and spectral resolution. While less accurate than the local terminator measurements obtained by SOIR on board Venus Express, aureole modeling has the advantage of being able to cover simultaneously a wide range of latitudes. We were able to favorably compare the aureole-derived vertical profiles to those obtained by SOIR during the transit itself (Pere et al. 2016, see also deliverable D8.2).

S6 - Mesospheric temperature derived from WP8, WP7, WP5 near terminator

CO2 has been observed in nearly all occultations, except at the beginning of the mission. To retrieve CO2 densities, all spectra recorded during one occultation are analyzed all together in an iterative way. From the CO2 density measurements, temperature is inferred using the hydrostatic equilibrium and therefore giving information on the thermal structure of the atmosphere. Based on a selection, the current VAST (Venus Atmosphere from SOIR measurements at the Terminator) model has been compiled. It is built on 122 orbits, during which several orders (i.e. wavenumber intervals) were recorded simultaneously allowing probing a large range of altitudes. However there are a lot more orbits during which CO2 was also observed but on a more restricted range. The individual observations (~500 orbits) are grouped in latitude bins, considering morning/evening difference but no distinction has been made between the Northern and Southern hemispheres albeit the analysis of the complete dataset should be possible in terms of North–South difference. Individual temperature profiles, inferred from the CO2 density profiles, are all characterized by a succession of minima and maxima. The existence of these minima and maxima, which are not present in the VIRA data, can be explained by radiative cooling and warming due to different CO2 bands active in the atmosphere (Mahieux et al. 2015).

The temperature profiles are nearly equal at 88 km and at lower altitude. However, the temperature reached at the first maximum at 10-2 mbar is different for morning and evening observations. Indeed, our
temperature maximum is lower by 23 K on the evening side than at the morning side. Piccialli et al. (2015) found similar temperature differences between the SPICAV-UV/VEx morning and evening observations at similar altitudes. This difference was also observed by Venera 15 at altitudes near 95 km (Zasova et al., 2007), indicating that at those altitudes the atmosphere was cooling during the daytime. The standard deviation of the temperature profiles are lower at these pressure levels: 12 K for AM and 20 K for PM. Above 100 km, the 2.5 10-5 mbar (~123 km) PM temperature minimum is located at a 6 km higher altitude (or at lower pressure levels) than the AM minimum, and reaches temperature of the same order (PM is 126 K and AM is 119 K). The 4 10-7 mbar level (~140 km) is also observed at slightly higher altitude in the PM profile (3 km, AM maximum temperature is 230 K and PM is 229 K, Mahieux et al. 2015). The differences between AM and PM temperature profiles can be explained by the different wind regimes at these altitudes: above 120 km, the subsolar to antisolar (SS–AS) circulation is predominant, while in the 90 km and 120 km a transition region is found between the SS–AS circulation and the retrograde atmosphere superrotation: winds at the morning terminator bring air from the hot dayside while they bring cold nightside air at the evening terminator. A latitudinal dependency is observed at both terminators. Highest temperatures are observed at near-equatorial latitudes decreasing towards the high latitudes and increasing again towards the poles. The highest temperature values in the southern hemisphere at the morning side of the terminator were taken during the campaign in April 2009. The IR-het data show a symmetry between the northern and southern hemisphere as it is also observed by the VIRTIS, SOIR and SPICAV instruments on board Venus Express.

Results in Krauze et al. (2016) are the first global study of dayside mesospheric temperature from ground-based IR heterodyne spectroscopy. The paper contains a comprehensive dataset of long term observations between 2009 to 2015 at the upper mesosphere/lower thermosphere providing temperature values at different locations of the morning and evening side of the terminator of the planet. Temperature information is obtained by line-resolved spectroscopy of Doppler broadened CO2 transitions features. Results are restricted to a pressure level of 1 μbar, ~110 km altitude due the nature of the addressed non-LTE CO2 emission line at 10 μm. The derived averaged temperatures from the IR-heterodyne spectroscopy are compared to results from three instruments on board Venus Express (VEx). A good agreement within the uncertainties with the temperatures from the VEx instruments SOIR, VIRTIS and SPICAV is found. Temperature values at the Venus terminators are in the range of 140 K to 240 K with a mean value of 192 K ± 20 K. A similar range is observed by the instruments on board of Venus Express (Gilli et al., 2015; Mahieux et al., 2015; Piccialli et al., 2015). Studies by VIRTIS-H over the entire day-side of Venus’ atmosphere in an altitude range of 100 km to 150 km also exhibit a temporal stable atmosphere over the time-frame of the VEX mission. These findings are in an excellent agreement with the IR-heterodyne observations.

S7 - Chemistry / Trace gas species (WP4, WP7)

Sulfur dioxide, a necessary precursor of H2SO4 droplets, was first identified in the upper atmosphere of Venus from ground based high resolution spectroscopy of Venus spectra in the range 299–340 nm (Barker, 1979). The same year, the stronger SO2 band at 208–218 nm was clearly identified with high resolution spectroscopy obtained with the telescope IUE (International Ultraviolet Explorer) by Conway et al. (1979). With the ultraviolet spectrometer UVS of Pioneer Venus, Stewart et al. (1979) identified also the
presence of SO2 in the UV reflectance (actually, ratio of reflectances at equator and polar regions) with two broad minima corresponding to the two UV bands of SO2. Later, the presence of SO was detected also with IUE (Na et al., 1990), which bands are mixed with SO2 bands in the region 200–220 nm. The most important and comprehensive previous Venus SO2 data set is the one extracted from eight years of UV reflectance recorded in 1978–1986 with UVS/Pioneer Venus (Esposito et al., 1988). One important feature of their study is the very large variability of observed SO2, ranging from 0 to 70–100 ppbv (at 40 mbar).

Comparison between Venera-15 IR data and Pioneer Venus data was also performed by Zasova et al. (1993). Another feature is the time decline of the SO2 amount (averaged over periods of about a hundred days), rather fast over the first year, and much slower later on. This behavior was interpreted as a massive “injection of SO2 into the Venus middle atmosphere by a volcanic explosion” (Esposito et al., 1988), as suggested earlier by Esposito (1984). Sulfur dioxide (SO2) is also an abundant minor species in the lower atmosphere of Venus – 150 ppmv as reported by de Bergh et al. (2006) – and thus an enormous quantity of SO2 is vertically convected up to levels where it can be observed from the outside (Bertaux et al., 1996).

With EuroVenus, we now obtained a new comprehensive database of observations to address this rapid and unexplained spatial and temporal variations of sulfur trace species at cloud tops. We have been using the TEXES high-resolution imaging spectrometer at the NASA Infrared Telescope Facility to map sulfur dioxide and deuterated water over the disk of Venus. Data have been recorded in two spectral ranges around 1348 cm⁻¹ (7.4 microns) and 530 cm⁻¹ (19 microns), in order to probe the cloud top at an altitude of about 64 km (SO2 and HDO at 7 microns) and a few kilometers below (SO2 at 19 microns). Mixing ratios are estimated from HDO/CO2 and SO2/CO2 line depth ratios, using weak neighboring transitions of comparable depths. All data show that the two molecules have a very different behavior. The HDO maps are globally uniform over the disk. The variations of the disk-integrated H2O mixing ratio (estimated assuming a D/H of 200 VSMOW in the mesosphere of Venus) varies by about a factor 1.5 over the four-year period. A constant value of 1.0 - 1.5 ppmv is obtained in most of the cases. The SO2 maps, in contrast, show strong variations over the disk of Venus, by a factor as high as 5. Long-term variations of SO2 show that the disk-integrated SO2 mixing ratio varies between 2012 and 2016 by a factor as high as 10, with a minimum value of 30 +/- 5 ppbv in February 2014 an a maximum value of 300 +/- 50 ppbv in January 2016. The SO2 maps also show a strong short-term variability, with a timescale of a few hours. In a separate study based on ALMA data, the HDO line is detected at each location observed on the disk on Nov. 26-27 2011. On Nov. 14 abundance presents a minimum (1 − 2 ppm) on the morning side, it increases during the day where it reaches a maximum value of ~6 ppm. H2O exhibits a strong depletion from the first to the second day. On the 15th of November two local maxima with values of ~2 – 3 ppm are observed close the evening terminator in the north hemisphere and at middle latitudes in the southern hemisphere, in general agreement with the TEXES values of 1.0 - 1.5 ppmv obtained in most of the cases.

Our final results can be summarized as follows:

- The HDO distribution is relatively uniform within the disk and shows limited temporal variations, on both short-term and long-term timescales. The mean disk-integrated H2O volume mixing ratio (assuming a D/H ratio of 200 x VSMOW in the Venus mesosphere) typically ranges between 1.0 and 1.5 ppmv.

- In contrast, the SO2 maps show strong variations over the disk, by a factor as much as 5. Short-term variations seem to have a time scale of a few hours. For intervals of about 2 hours, the SO2 features at the cloudbase often shown to follow the 4-day rotation of the clouds. We have no confirmation of short-term (i.e. shorter than an hour) variations of the SO2 maps at 19 μm. We believe that these maps have to be considered with caution because of possible fluctuations of the continuum curvature over the map.

- Data are consistent with a cutoff in the vertical distribution of SO2, with no SO2 above a level situated a few kilometers above the cloudbase. The exact altitude of this level depends upon the thermal profile used in our calculations. In addition, our data show little sensitivity to the exact altitude of this level. A higher spectral resolution would help to better constrain this level.

- The TEXES data are consistent with a constant vertical distribution of H2O. Whereas a cutoff as observed for SO2 can be excluded in the case of H2O, the TEXES sensitivity, however, is not sufficient to discriminate between a constant water mixing ratio throughout the mesosphere, and a moderate depletion by a factor of 2 at about z = 85 km, as suggested by photochemical models (Zhang et al. 2012).

- The SO2 mixing ratios (calculated assuming a cutoff at a constant altitude for all datasets) show a variation by a factor of 10 between 2012 and 2016. The minimum value is observed in February 2014 while the maximum value is found in January 2016. It should be noticed that, because of our limited spectral resolution, the TEXES data are sensitive to the column density of the minor species rather than their mixing ratio at a given level. We still convert this quantity into a mixing ratio at the cloudbase for an easier comparison with other datasets.

Results on the temperature structure derived from ALMA observations and analysis were presented at the Oct. 2015 AAS/Division of Planetary Science meeting held in National Harbor, MD, and at the International Venus Conference in Oxford, 4-8 April 2016. After Encrenaz et al. (2015), a new peer-reviewed publication on the thermal structure of the Venus mesosphere in sub-millimeter wave is submitted (Piccialli et al.). The maps of CO, SO, SO2 and HDO retrieved with ALMA allowed for the first time a comparative analysis of the behavior of mesospheric species and there daily variations. It is interesting to note that all four maps have different characteristics. The map of the CO line depth (sensitive to the CO vertical distribution and the temperature profile in the mesosphere) is globally symmetrical, and shows no evidence for day-night variations (except possibly in the core, where altitudes as high as 100 km...
are probed). The SO and SO2 spatial distribution, in contrast, show significant variations at the day time scale.

Trace gas species have also been studied using SOIR data (WP7). During the time of the EuroVenus project, the density and derived volume mixing ratios (vmr) profiles of all trace gases recorded with SOIR during the whole VEX mission were obtained; this analysis includes CO, HCl, HF, SO2, H2O and HDO vertical abundances. Since the abundance of SO2 in the Venus atmosphere is quite close to the SOIR SO2 detection limit, we developed a specific method to clearly indicate positive observations and performed a very detailed sensitivity study. Improvements in instrument calibration, data reduction and a long base line of data allowed the analysis of the whole data set, including the retrievals of water vapour in the mesosphere, for which the wavenumber-pixel calibration is much more complicated than for other species. These results will be included in the new version of the Venus International Reference Atmosphere (VIRA). The retrieval technique to derive the density of CO, HCl, HF, H2O and its isotopologue HDO is the same as for CO2 densities. CO2 has been observed in almost all occultations, except at the beginning of the mission, when we did not realize the high variability of the Venus atmosphere and therefore the need to measure CO2 during each occultation. Knowing the CO2 density allows us to derive volume mixing ratios (vmr) of all trace gases. Since the abundance of SO2 in the Venus atmosphere is quite close to the SOIR SO2 detection limit, we developed a specific method to clearly indicate positive observations and performed a very detailed sensitivity study. This study was limited to the measurements recorded from the beginning of the mission up to February 2013 (up to orbit 2500). This limited database counts 137 solar occultations potentially containing a SO2 signature of 93 present a positive detections representing 68% of the occultations. For H2O and HDO retrievals, we refer to report on deliverable D7.5.

CO observations have been performed during the VEx mission and have been investigated focusing on the short and long term variation and the latitudinal dependence. Considering latitudinal bins definition and separating for AM and PM observations, averages are also obtained for CO. At high altitudes (above 120 km), the agreement with VIRA is better than at lower altitudes. Moreover, a morning/evening difference is also clearly observed, with lower values at the morning terminator than at the evening one. This trend is however reversed at lower altitudes. Densities are systematically lower than VIRA at low altitudes. The scale heights are also quite different. In fact, three zones are apparent in the SOIR profiles: Below 90 km, the scale height is almost constant with value ranging between 3 and 9 km (average value of 6 km) depending on the particular orbit. Between 95 and 110 km, the scale height is slightly increasing, from values of 6 to 12 km, AM scale heights being somewhat lower than PM values: from 8 to 10 km for AM, and from 9 to 12 km for PM. Then, above 115 km, the scale height is decreasing to reach values around 6 km at 140 km (Mahieux et al., PSS, 2015a, 2015b; Vandaele et al., PSS, 2015).

S8 - Aerosols model simulations

The targeted altitude range depends, amongst others, on the wavelength of the measurement; it is typically 70-95 km with the SOIR and SPICAV-IR channels and 90-105 km with the SPICAV-UV channel. Therefore the overlap in altitude range covered by the 3 spectrometers is very limited. The very different shape of the extinction profiles between North Pole and Equatorial observations are not atmospheric and are purely due the very elliptical shape of the VEx orbit around Venus with the perigee being above the
North Pole. The fine-structures in the extinction profiles often observed at high Northern latitudes are completely smoothed out at other latitudes because the vertical resolution deteriorates with distance from the North Pole.

Extinction due to aerosols can be derived routinely from SOIR spectra. As the aerosol signature is a continuum of absorption, the impact of aerosols on the observed spectra is therefore a decrease of the mean transmittance levels, the baseline of the spectra, with decreasing altitude. As a result the continuum is obtained by fitting the baseline of a spectrum. Vertical profiles of the extinction can be retrieved from virtually each diffraction order of the SOIR instrument, as far as the spectra are not spectroscopically saturated in the targeted range of altitudes. Applying the onion-peeling method, i.e. the atmosphere is considered as an onion-like structure composed of successive homogenous spherical layers, leads to the determination of the local extinction \( b \) in each atmospheric layer. The variations in aerosols loading can then be compared to other parameters retrieved from the same SOIR spectra such as water and SO2 composition or temperature (when the selected spectral windows of the observation allow it).

An independent analysis of the extinction coefficients from the three channels for a limited number of observations (Wilquet et al., 2009) and a recent analysis of the SPICAV-IR data (Luginin et al., 2016) demonstrated that a Mie based optical model of submicron particles consisting of concentrated sulfuric acid (75%) is not sufficient to explain SPICAV/SOIR observations of the Venus upper haze. The particle size distribution and the concentration of sulfuric acid in the droplets can be estimated from the spectral dependence of the extinction coefficients. A subset of 49 observations for which the retrieval of the extinction coefficients with the SPICAV-IR channels is of good quality and concomitant SOIR observations are available have been analysed. These results are promising, however for some observations, none of the tested size distributions integrated in the optical model can satisfactorily fit the experimental values of the extinction. As mentioned in Luginin et al. (2016), it is not sure in the case of unimodal size distribution if SPICAV-IR and SOIR are not just ‘blind’ towards particles of 0.10-0.15 µm when the concentration of bigger particles reaches a certain level (Wilquet et al., in preparation).

S9 - ISSI group

The International Space Science Institute (ISSI) has provided a venue for comparison and cross-validation of results from different RTD work packages in RP1 (Nov. 2013, June 2014) and RP2 (January 2015). Participating scientists in Cologne (RIUUK : M. Pätzold, S. Tellmann), in Paris (OBSPARIS : T. Widemann, T. Encrenaz, A. Piccialli) and Brussels (IASB-BIRA : A.C. Vandaele, A. Mahieux) of the EuroVenus consortium were co-investigators of ISSI research teams "Venus Thermal Structure" research team coordinated by S. Limaye. EuroVenus participants in Brussels (IASB-BIRA : A.C. Vandaele, W. Wilquet) and Oxford (UOXF : C. Wilson) are members of the 2013-2015 International Space Science Institute (ISSI) team "Improved Understanding of Venus Clouds" coordinated by E. Marcq and C. Wilson. The ISSI meetings are closely associated with the completion of EuroVenus WP2 objectives and deliverables and therefore were supported by the EuroVenus project. The publication outputs of the ISSI groups reflect the comparison and cross-validation effort developed in the framework of WP2 Task T2.2. Since the publication of the Venus International Reference Atmosphere (VIRA) in 1985, Venus Express orbiter has obtained vast amounts of new data about the Venus atmosphere which extends knowledge of the atmospheric vertical structure to about 150 km from a variety of in-situ and remote sensing
experiments/observations, while at the same time many ground based experiments have provided data on
the upper atmosphere temperature structure. The final ISSI publication presents results of atmospheric
structure comparison in five latitude bins (0° – 30°, 30° – 50°, 50° – 70°, 70° – 80° and 80° – 90°
latitude) and three local times – Day (7 h -17 h), Night (19h – 05 h) and terminator regions (5 h – 7 h and
17 h – 19 h, Limaye et al., in revision).

Conclusions

The EuroVenus FP7 G.A. 606798 project has fully achieved its objectives and technical goals. The main
results of the project are an enhanced climatology of the Venus atmosphere and the delivery of high level
data products to the planetary science community worldwide. The exploitation and interpretation of Venus
Express instruments and ground-based observations have considerably increased our knowledge of the
Venus atmospheric thermal structure above ~40 km and provided new information above 100 km. One of
the major goals of the Venus Express (VEx) mission has focused upon increasing our understanding of the
highly variable global circulation and wave processes impacting the Venus mesosphere-thermosphere
(~80 – 200 km). Several VEx instruments (e.g. SOIR, SPICAV and VIRTIS) and ground based
observations have provided measurements that characterize the upper atmosphere structure, trace gases
chemistry and underlying variable dynamics. As an example, a EuroVenus team led by P. Machado has
evidenced the meridional wind circulation at cloud-top in both dayside hemispheres (Machado et al. 2016).
Considerable variability in the temperatures and densities is seen above 100 km but certain features
appear to be systematically present, such as a succession of warm and cool layers. Modeling studies
support the existence of such layers in agreement with a global scale circulation and the maintenance of
atmospheric superrotation.

A major event during the period has been the end of mission of Venus Express in January 2015 after the
spacecraft went out of fuel in December 2014. The scientific impact of the end of the Venus Express
mission in Dec. 2014 was minimized by the exploitation of redundancy between ground-based
instruments, and between VEx instruments, and their previous intercomparison by our teams. Specific
science campaigns of most relevance to this research project had already been included in the Science
Activity Plan of Venus Express to occur in 2014; these included campaigns dedicated to solar occultation,
radio occultation, mesospheric sulphur dioxide and South polar dynamics. These campaigns had been
scheduled for coordination with EuroVenus ground-based observers by ESA. Work performed during the
reporting period addressed a wide range of targets at all altitudes in Venus' atmosphere, from atmospheric
dynamics and chemistry to upper atmosphere studies and solar wind interaction. The solar, stellar and
radio occultation investigations in particular have provided a far more detailed view of mesospheric
processes and thermal structure than had been obtained from previous missions. For the first time, the
intercomparison of the ground-based and VEx results provides a consistent picture of the temperature and
density structure in the 40 km - 180 km altitude range.

The Venus Express observations have considerably increased our knowledge of the Venus atmospheric
thermal structure above ~40 km and provided new information above 100 km. There are however still
observational gaps in latitude and local time above certain regions. Based on the exploitation of past
Venus Express measurements, the project has successfully performed coordinated observations of Venus
using different techniques, to provide a detailed analysis of dynamical and chemical couplings between
different levels of the atmosphere that are probed simultaneously by different instruments. This large ensemble of results have been presented in several international conferences. Each partner beneficiary has prepared an archive of high-end products available in their home institute on a proprietary server, and prepared an agreed query/format documentation to make them accessible from the main project website at www.eurovenus.eu.

Potential Impact:

IMPACT

I1 – Impact in the science and engineering community

EuroVenus is a partnership reference in Europe’s planetary science community. As a consortium, it has co-authored most recent publications on the next steps of future Venus exploration. Intense relationship with the planetary science community is very strong as assessed by the presence of our consortium in international conferences (EGU meeting in Vienna, AAS/DPS meeting in the US), International Space Studies Institute workshops in Bern. After the end of the Venus Express orbital operations in 2015, several space agencies including CNES, ESA, and NASA, have discussed the possibility or sending future missions to planet Venus. By attending international meetings to disseminate lessons learned from EuroVenus consortium activities, our consortium has summarized lessons learned from VEx data analysis and the other WPs of EuroVenus activity, to feed forward into science requirements for future scientific investigations of Venus. Higher-level data products, such as wind vectors and temperature & aerosol vertical profiles have been gradually made available, firstly for internal dissemination of data within the team, and secondly for distribution to the public through the EuroVenus project website. This large ensemble of results have been presented by all consortium participants at the EuroVenus-sponsored International Venus Conference held in Oxford on April 4-8, 2016, as well as later conferences, and shared with the modeling community, ensuring that the benefits of the EU funding will be felt beyond the end of the funded period.

A new spacecraft has arrived at Venus in Dec 2015: Japan’s Akatsuki, or Venus Climate Orbiter. This small satellite carries a suite of cameras designed to study the meteorology of Venus at a number of altitude levels. Its near-equatorial orbit will yield data complementary to those from the polar-orbiting Venus Express. This has offered the EuroVenus project new opportunities for joint / coordinated observations. A new international campaign is in preparation for the next cycle of Venus maximum elongations (East, Jan 12, 2017; West, June 3, 2017). After Akatsuki, there are no confirmed missions, but many proposals for spacecraft to investigate Venus’ geological history and pursue European advances on Venus research. A EuroVenus task is dedicated to Science Definition for Venus exploration missions, ensuring that European Venus scientists have taken part in exploitation of data from future Venus missions led by other agencies. The European proposal for a new mission to Venus, EnVision, has been proposed by two EuroVenus core participants (T. Widemann, C. Wilson) in response to ESA 5th call for a M-class mission (M5). NASA/Discovery mission proposal to Venus (co-I T. Widemann) is in final selection for a possible launch in 2022.

I2 – Institutional impact on beneficiary institutes

At Oxford, the EuroVenus consortium funding has supported salary costs for Dr. Wilson. The experience
he gained during these EuroVenus-funded years helped him to be awarded a prestigious UK Space Agency Fellowship, which will now fund him in the 2016-2020 period to work on Europe’s Mars exploration programme. EuroVenus funding has therefore proved important in keeping Dr. Wilson within European planetary science. In addition to EuroVenus outputs already reported, Dr. Wilson has played an active part in teaching and supervision of students and other contract research staff. In addition to Oxford University students he was able to supervise a 5-month Masters thesis research project by a visiting student from Sweden, working on analysis of upper atmospheric densities from Venus Express’ torque measurements, and another 5-month study on intercomparison of VEx radio occultation with VEx UV imagery conducted by a Dutch postdoc (the postdoc was not funded by EuroVenus). Dr. Wilson was able to serve as a Guest Editor for a Special Issue of Planetary Space Science issue, published in June 2015; he is also on the editorial board for a forthcoming “Venus III” book, which attempts to summarise current state of knowledge including outputs from the EuroVenus project. Through this, and through his organisation of the EuroVenus-supported Venus conference in Oxford, Dr. Wilson has been able to support European leadership in planetary science (particularly in Venus science).

In Lisbon, the EuroVenus project allowed to stabilize and consolidate the research on Planetary systems - Solar system. In the framework of the Institute of Astrophysics and Space Sciences, the planetary atmospheres research developed by the EuroVenus team gave strength to the planetary systems’ research field, which now has become a strategic thematic line of this Institute. Along the project, several fruitful collaborations were started and enhanced, in the domain of planetary atmospheres, with other project partners, as is the case of the on-going collaboration with Paris Observatory. On the other hand, the work done in the framework of EuroVenus, allowed to develop and fine-tune Doppler and cloud-tracking methods for atmospheric dynamics studies, that turn our group highly competitive in the field of atmospheric studies. As a direct consequence, it was possible to start new collaborations with the Sanchez-Lavega team (Bilbao, Spain), with Paolo Tanga from Nice observatory and with the Japanese Akatsuki space mission (on-going work).

In the Belgium Institute for Space Aeronomy, the impact of EuroVenus funding is observed first in the long list of presentations at international conferences with a peak in 2014, which is then translated in peer-reviewed publications in the following years. On the long-term, this has helped the team at IASB-BIRA to improve our visibility and to build an international reputation in the field of Venus atmospheric research and more generally of planetary aeronomy.

In Nice, the EuroVenus project has permitted to start a fruitful collaboration concerning planetary atmospheres, in contact with the other partners. It was thus possible to have a considerable amplification of the science return of the Venus Twilight Experiment. This experience was built before the transit of Venus in 2012, and was at the origin of the partnership with Nice in the frame of EuroVenus. The processing and interpretation of the data obtained during the transit, from space and from the ground, has brought to Nice a solid expertise in this domain, that can be exploited in the future in the general situations concerning transits and occultations by bodies with an atmosphere.

In Cologne, EuroVenus funding provided the financial support to hire (1) a PhD student who worked on the analysis of thermal infrared heterodyne (THIS) data. During the time of the project, the PhD student analyzed the former and recent THIS data and developed a new method to calibrate the entire data set.
The recalibrated data set has a much higher accuracy than the former data set and builds now a well-established data base for comparison with other ground-based and space-based Venus atmospheric data. (2) a PhD student who developed a new method for the multipath correction of VeRa radio science data. This new method is fundamental for the interpretation of the VeRa data in the cloud layer. It was found that the corrected data set reveals a colder tropopause than previously expected. This multipath analysis method is a valuable tool for future missions to other planets that also exhibit multipath effects like the JUICE mission to Jupiter; (3) a PhD student who worked on the analysis of sulfuric acid concentrations in the Venus cloud layer. He developed a new method to use this data set for the understanding of the global Venus circulation. A global picture of the sulfuric acid concentrations in the Venus cloud layers is a powerful tool to unravel the global circulation on Venus.

I3 - Website and on-line contents

The website for the EuroVenus project http://www.eurovenus.eu is now fully operational and online. It presents the teams’ science activities, results from the consortium and news and updates on present as well as future projects for the spatial exploration and study of planet Venus, our nearest neighbour. The site includes links to partner Institutes and European teams, a presentation of reasons to explore and study Venus, and links / outreach material for dissemination toward a larger public. It is hosted and maintained at the main beneficiary’s institute (Paris Observatory/LESIA). It has all functionalities foreseen in the DoW:

- a presentation of the European space program, REA and EU FP7-SPACE program,
- facts about Venus, the atmospheric circulation and photochemistry,
- facts about observational methods from the ground and from space,
- a description of the Venus Express mission,
- a presentation of the EuroVenus project,
- a description of Venus Express instruments and results,
- EuroVenus work packages, and links to main telescope facilities used in the framework of the consortium,
- a clickable link to project outputs, raw data and higher data products,
- short educational films produced in the framework of the EuroVenus consortium,
- a 52-minute feature-length film,
- biography of project participants.

I4 - Preserving high level data and disseminating project results

The outputs page of the EuroVenus project website contains permanent links to higher level data products, as described in deliverable D3.10. Each partner beneficiary has prepared a selection of high-end products available in their home institute on a proprietary server, with an agreed query/format documentation to make them accessible from the main project website. This context, the nature of data products, and co-authorship issues for database users have been addressed in the Archive Definition Document (Deliverable D3.9).

VEx/SOIR: The ESA PSA contains Level 2 (raw spectra) and Level 3 (calibrated spectra). Vertical profiles
of CO2 density, temperatures, trace gas abundances and light extinction due to aerosols from the SPICAV-SOIR (Solar Occultation in the InfraRed) experiment are publicly available from the Belgian Institute of Space Aeronomy webpage here: [http://venus.aeronomie.be/en/soir/soir_data.htm](http://venus.aeronomie.be/en/soir/soir_data.htm). The website includes documentation, and observation database and tools for accessing the data.

VEx/VeRa: The ESA PSA contains Level 1 (raw) and Level 2 (calibrated Doppler frequency residuals) for the Venus Express Radio Science experiment. Higher Level 4 (individual profiles of neutral density, pressure and temperature) and Level 5 (binned by latitude and Local Solar Time regions) data will be made publicly available from the University of Cologne’s web server here: [http://www.radio-science.eu/?page_id=746&lang=en](http://www.radio-science.eu/?page_id=746&lang=en). Data currently available here include Level 5 binned data; Level 4 profiles will delivered by Oct 2016.

VEx/VIRTIS: The ESA PSA contains Level 2 (radiances in Data Numbers) and Level 3 (radiances calibrated in scientific units) data. As part of the EuroVenus research, wind vectors are being obtained on the basis of feature tracking from VIRTIS data. Data will be released both in the form of 2D vector fields, as well as latitude profiles of 2D wind velocities. These products will be made available on a web server at the University of Lisbon, accessible either directly or via the Europlanet Virtual Observatory system.

2012 Venus transit observations and derived products:
Raw data for EuroVenus research of the transit was available from three observatories: Hinode satellite, raw data publicly available from [http://sdc.uio.no/sdc/welcome](http://sdc.uio.no/sdc/welcome); Solar Dynamics Observatory, raw data publicly available from [http://jsoc.stanford.edu](http://jsoc.stanford.edu); Venus Twilight Experiment, [http://venustex.oca.eu/](http://venustex.oca.eu/)

I5 - Educational films, news and documentaries

The project has fully accomplished its program of educational film outreach. Over the duration of the project RP3 it has concluded a series of six short educational films (10-15 minutes long), describing each of the activities included in the EuroVenus project and their synergies (communication target 1,2). Segments have been filmed at a range of locations including telescopes, ESA sites, and potentially Venus-like locations. It has also provided a feature-length documentary, prepared through filming EuroVenus participants about Venus and Venus Express, highlighting role of ESA and European ground-based observers. In addition, short (2 min) news video were recorded and disseminated online every 3-4 weeks (communication target 1,2). Outreach activities in the framework of EuroVenus project and the Venus Express mission have been filmed in 2014 and broadcast / webcast on two major European TV channels segments ARTE-TV and EuroNews-SPACE in September 2014. Both segments have evidenced the importance of History of Venus exploration and the figure of Venus as a planet in the Earth's sky as a support to dissemination of Venus Express science from ESA and EuroVenus consortium activity and outreach. In particular, the "SPACE" broadcast on EuroNews hoisted by Jeremy Wilks was filmed in September 2014 in the main institute of the EuroVenus project, Paris Observatory. This particular broadcast has been advertised on Paris Observatory's home page as well as on ESA main site at [http://www.esa.int/ESA](http://www.esa.int/ESA).

All products are available on the EuroVenus project website.
The films produced by White Fox Pictures for the consortium went beyond the basic requirements of conveying information about the consortium’s activities; they also are visually attractive and appealing for a wider public than normally targeted by such films. As testament to this, the project’s youtube channel via which these films are released has by now amassed almost five thousand views. In addition we were able to produce a novel outreach product: a 360-degree film viewable using Virtual Reality headsets, allowing the viewer to visit (in VR) the large telescopes in Hawaii used by EuroVenus researchers during the course of their observations in Jan 2016. This film, produced at the very end of the consortium’s activities, has proved very appealing at outreach events – see for example image below – and it will be used at many more such events in future; in addition, it can be downloaded by users to view on their own equipment. It has been distributed on youtube and facebook and has already accumulated well over 20,000 views. All of these outreach products, as well as consortium information, are publicised via the project website (www.eurovenus.eu) which has also proved highly successful.

Deliverable Episode Direct link on the Address number number public project site on youtube

D3.2 episode 1 http://eurovenus.eu/News/51/ https://www.youtube.com/watch?v=rk7GTzZGpNU
D3.3 episode 2 http://eurovenus.eu/News/64/ https://www.youtube.com/watch?v=pl4bE3xSo1g
D3.4 episode 3 http://eurovenus.eu/News/66/ https://www.youtube.com/watch?v=3STtwIinwrMg
D3.6 episode 5 http://eurovenus.eu/News/71/ https://www.youtube.com/watch?v=c1h_-6BDdJk
D3.7 episode 6 http://eurovenus.eu/News/72/ https://www.youtube.com/watch?v=H7fg7PTFIYE

I6 - Conference activity and events

EuroVenus is a partnership reference in Europe’s planetary science community. As a consortium, it is coauthor of most recent publications on the next steps of future Venus exploration. Intense relationship with the planetary science community is very strong as assessed by the presence of our consortium in international conferences (EGU meeting in Vienna, AAS/DPS meeting in the US), International Space Studies Institute workshops in Bern. An international conference in Oxford University (April 2016) has brought together 130+ Venus scientists from across Europe and the international Venus community.

This has been an efficient way of supporting and growing the European Venus Science community, by providing an event for the exchange of ideas between researchers, especially younger researchers. It has therefore been especially valuable as a method of capacity-building for the future, to ensure that the benefits of the EU funding are felt beyond the end of the funded period.

List of Websites:
Address of the action’s public website and related information: http://www.eurovenus.eu
Last update: 19 June 2017
Record number: 199375