Abstract Book

Session 1: Mission overview and status – oral talks

EnVision Objectives and Mission Status

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Abstract

After its successful Venus Express mission (2006-2014), ESA selected EnVision as its 5th Medium-class mission in the Agency's Cosmic Vision plan, targeting a launch in November 2031. The mission is a partnership between ESA and NASA, where NASA provides the Synthetic Aperture Radar payload and DSN support for critical mission phases, while ESA is responsible for the overall mission.

Recent modelling studies strongly suggest that the evolution of Venus' atmosphere and interior is coupled. The EnVision orbiter will be the first mission to investigate Venus as a system, characterizing the interactions between the planet's interior, subsurface, surface and atmosphere. This holistic approach allows to study the planet's History, Activity and Climate, characterizing Venus' core and mantle structure, investigating past and present geologic processes shaping its surface and atmosphere, and to look for evidence of past liquid water.

To fulfil its science objectives, EnVision employs a suite of instruments optimised for observations from Venus orbit, including an imaging radar for high-resolution surface mapping, a sounding radar for discerning the geometry of the near subsurface, a multispectral infrared camera capturing the composition of surficial rocks, and an infrared and ultraviolet spectrometer, complemented by radio science experiments, to identify the pathways of important volcanogenic gases from the lower atmosphere up and into the clouds and beyond, and precise orbit determination to measure the gravity field and probe the deep interior structure of Venus.

The mission is currently in phase B1, and targets an adoption by ESA Science Programme Committee (SPC) early 2024, for a start of mission implementation end of 2024. The presentation will give an overview of the mission science goals, the current mission baseline, its status, challenges, and next milestones on the road to launch.

EnVision science ground segment and operations planning

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Abstract

EnVision is a mission requiring both global and targeted observations. A large collection of potential regions of interest, representative of different features, and covering all latitudes and all longitudes have been defined and will be selected according to the final mission profile.

Many of the observations will be repeated to detect temporal variations, and regions of interest will be observed with multiple modes and measurements.

The presentation will describe the approach to science operations planning and the challenges of

- planning observations with requirements on minimum track spacing; sequential orbits, illumination conditions; repeat look angle and repeat travel direction
- scheduling observations on a spacecraft with a fixed high gain antenna and thermal constraints
- finding opportunities from an inertially fixed orbit around a slowly rotating planet, with a large variation in data rate (dependent on the Earth-Venus distance).

Session 1: Mission overview and status – posters

ProVISION: Employing Prolog in rule based science operations planning

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Abstract

The EnVision mission poses particular challenges on science operations planning. A key goal is the *repeated* observation of regions of interest (ROIs) to detect changes. The observations have to be performed under well defined geometric and illumination conditions. On the other hand, the relatively short spacecraft orbital period and the requirement to suspend any scientific observations for the downlink of acquired data to Earth makes it difficult to reconcile downlink periods with observation periods.

So far, we had developed a SPICE based tool called Envisionary which allows to compute events of ROI coverage, illumination on the planet's surface and on the spacecraft, downlink opportunities, and other geometric conditions. Envisionary is orchestrated in a functional programming manner which allows lazy evaluation. Therefore, it can efficiently handle geometry computations with a small ten seconds time step over the whole mission duration. The resultant event files serve as input for the Mission Analysis and Payload Planning System (MAPPS), which is then used to generate timelines of instrument operation.

Before being fed into MAPPS, the event files from Envisionary need to be filtered according the certain criteria. E.g., we only want to consider a certain selection of ROIs or a certain cycle (a count of Venus siderial days). While we started out with using a simple tool like the famous grep from the *nix world, it turned out that interdependencies require more complex rules that cannot be handled in this way.

When we realized that we have to deal with complex interdependent rules, the idea that the logic programming language Prolog could be useful came up. Prolog is well suited for tasks that benefit from rule based logical queries. It can import one or more knowledge bases which contain facts and rules and then it can be queried for entities that fulfill certain conditions.

For a preliminary investigation, we have created Prolog knowledge bases from the output of Envisionary. Already with quite simple queries, we can extract very useful information like a list of orbits in which a certain ROI can be observed under given geometric conditions without interfering with any downlink opportunity. We will show examples and discuss further development.

Session 2: Science payloads and experiments – oral talks

The VenSpec suite on the ESA Envision mission – a holistic investigation of the coupled surface atmosphere system of Venus

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Abstract

The ESA EnVision mission will determine the nature and current state of Venus' geological evolution and its relationship with the atmosphere, to understand how and why Venus and Earth evolved so differently. Perched at the inner edge of the Sun habitable zone, Venus may once have been habitable, with liquid water oceans, before developing the enormous greenhouse warming which renders it uninhabitable today, thus providing a natural laboratory for studying the evolution of habitability. Venus is Earth's closest sibling geologically: similar in size to the Earth, it has remained active into the present era, unlike the much smaller Mars and Mercury. Venus is essential for understanding the links between planetary geophysical evolution and habitability of terrestrial planets from our own Earth to terrestrial planets and exoplanets everywhere, including those which will be the subject of study by PLATO and ARIEL missions in ESA's Space Science programme.

The VenSpec instrument suite is following the holistic approach of the EnVision mission by studying the coupled system of surface and atmosphere on Venus with three complementary instruments. In combination, VenSpec will provide unprecedented insights into the current state of Venus and its past evolution. VenSpec will perform a comprehensive search for volcanic activity by targeting atmospheric signatures, thermal signatures and compositional signatures, as well as a global map of surface composition. A joined VenSpec science team across the whole suite ensures that the synergies between the instruments are fully used.

VenSpec-U will monitor sulphured minor species (mainly SO and SO_2) and the as yet unknown UV absorber in Venusian upper clouds and just above. It will therefore complement the two other channels by investigating how the upper atmosphere interacts with the lower atmosphere, and especially characterize to which extent outgassing processes such as volcanic plumes are able to disturb the atmosphere through the thick Venusian clouds.

VenSpec-H will be dedicated to high resolution atmospheric measurements. The main objective of the VenSpec- H instrument is to detect and quantify SO2, H2O and HDO in both the troposphere and the mesosphere, to enable characterization of volcanic plumes and other sources of gas exchange with the surface of Venus, complementing VenSAR and VenSpec-M surface, SRS subsurface observations and VenSpec-U observations in the upper cloud layer.

VenSpec-M will provide near-global compositional data on rock types, weathering, and crustal evolution by mapping the Venus surface in five atmospheric windows. VenSpec-M take advantage of the improved altimetry provided by the NASA VERITAS VISAR and Envision VenSAR-derived DEMs. VenSpec-M will monitor for H2O abundance variations close to the surface complementing VenSpec-H observations. In combination with the observations provided by the identical VEM instrument on the NASA VERITAS mission VenSpec-M will provide more than a decade of monitoring for volcanic activity, as well as search for surface changes.

VenSAR: A Fresh Look at Venus' Surface

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Abstract

The EnVision VenSAR radar would be designed and built by NASAs Jet Propulsion Laboratory, and is a reflectarray antenna concept consisting of a 6.0×0.6 meter reflector antenna illuminated by 1.0 meter feed separated by a distance of 2.75 m. Its design was motivated by mass and size considerations, the ability to support multiple modes of operation and a desire to operate with a frequency similar to Magellan. The antenna is a piecewise planar approximation to a parabolic reflector designed to achieve good sidelobe performance over the entire 60 MHz transmitted bandwidth. The VenSAR modes of operations are:

- **SAR Modes**. In the medium resolution stripmap SAR mode the radar transmits a 15.5 MHz band-width signal to enable 30 m ground resolution imaging of the surface with a swath width of 57 km. VenSAR collects data with incidence angles between 20˚ and 40˚ depending on altitude (between 220 km and 540 km) with noise equivalent $\sigma_o \leq$-20 dB. Data from 25-30% of the surface are expected to be acquired mode. In the high resolution stripmap SAR mode the radar would transmit a 60 MHz bandwidth signal to acquire 10 m ground resolution imaging of the surface with a swath width of 20 km. Data from 2- 5% of the surface would be acquired in this mode. Both modes can optionally collect data in a dual polarization mode where both HH and HV data are obtained.
- **Altimeter Mode.** In the altimeter mode, the radar would be pointed nadir with the long direction (azimuth) of the antenna oriented perpendicular to the flight track. By transmitting 60 MHz bandwidth the radar pulse limited footprint after Doppler beam sharpening is about 3 km. Altimeter data would generate nearly globally distributed topographic measurements of the surface of Venus with an elevation precision of about 20 m and an along-track spacing of 3 km. Spacing at the equator would be roughly 40 km.
- **Radiometer Modes.** In the VenSAR radiometer modes passive microwaves emitted from the surface of Venus are collected and used to derive surface emissivity, which in turn can be used to determine surface properties like roughness and dielectric constants. VenSAR would record H and V polarization data allowing polarimetric emissivity measurements. The VenSAR radiometer is designed to have brightness temperature accuracy of 1.7K and a brightness temperature precision of 0.7K with a spatial resolution of 30-40 km.
- **SAR Stereo Mode**. Radar stereo or radargrammetry uses image displacements or parallax measurements between radar images acquired at different incidence angles to solve for topography. Stereo pairs with incidence angle differences of roughly 5˚-10˚ would be used to generate topographic data with a spatial resolution of 240 m and an elevation accuracy of 25-50 m.

A portion of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The information presented about EnVision is pre-decisional and is provided for planning and discussion purposes only.

The Radio-Science experiment onboard EnVision

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Abstract

The Radio-Science experiment of EnVision comprises two sub-experiments (the Gravity experiment and the Radio-occultation experiment) that both relies on the Telemetry, Tracking and Command (TT&C) system of the spacecraft but that have different scientific goals and different operation modes.

The internal structure of Venus is still uncertain (size and state of the core, mantle viscosity, average lithospheric and crustal thicknesses, as well as their lateral variations). These are key parameters to constrain the mantle composition, thermal evolution and deep interior of the planet. Without the availability of seismic data and Venus having no internal magnetic field, the gravity field is the only tool that can be used to determine the radial structure of a planet. Thanks to its 6 cycles mission, the EnVision gravity field solution will improve the Magellan solution by providing a better global degree strength as well as areas of higher resolution. The location of these areas depends on the pericenter position of the science orbit. These will allow to study topography/gravity ratios over structures of interest to understand their crustal and lithospheric morphologies. It is also expected that the k_2 tidal potential Love number precision will be better than 1% (compared with the 22% for the Magellan solution [2]), which will result in an improved constraint of the state and the size of the core [3].

Radio-occultations will be performed to derive the atmospheric structure (temperature, pressure, number density) and the electron density profile of the ionosphere of Venus. Thanks to the addition of a Master Reference Oscillator (BHE, Hungary) in the payload, the experiment will be performed in a one-way mode, allowing to probe the atmosphere down to 35 km both at ingress and egress. Although a lot of radio-occultation experiments have already been performed by Venus Express [4,5], the short orbital period of EnVision (1.5 hours instead of 24 hours for VEx) and its near polar orbit will allow to cover a wide range of latitudes, longitudes and local times as well as to observe short-term variations of the temperature and pressure profiles caused by atmospheric waves. Moreover, the use of a dual X and Ka band communication link will enable for the first time to estimate both liquid and gaseous phases of H_2SO_4 at the base of the clouds. SO_2 profiles at 45-55 km will also be derived, allowing a synergy with the measurements of VenSpec-H. H_2SO_4 and SO_2 estimates are of a great importance to better understand the sulfur cycle and, in consequence, its potential link with the planet activity.

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Subsurface Radar Sounder for the analysis of the Shallow Venus Subsurface

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Abstract

EnVision, selected as the ESA's Cosmic Vision 2015-2025 M5 medium-class mission, aims to explore the present-day activity, the geological history of the surface and the hostile climate of Venus. It will carry on-board the Subsurface Radar Sounder (SRS), an orbital ground-penetrating radar, aimed at searching for subsurface structures and addressing crucial science questions on the evolution of the Venus surface and shallow sub-surface. Moreover, SRS will provide surface altimetry measurements and will search for possible lighting activity in the Venus atmosphe re (which could be an indicator of active volcanism).

The main geological targets of the scientific objectives related to the surface and shallow subsurface of SRS are: 1) buried and modified impact craters, to determine the nature and thickness of the imp act infilling, 2) stratified units, to understand their stratigraphic relationships, 3) tesserae highlands, to investigate their 3D geomorphology and potential buried structures, 4) plains, to estimate their dielectric properties, 5) lava flows/fields, to estimate their roughness, dielectric properties and range of thickness for constraining their modes of emplacement.

SRS design and operation strategy is based on maximizing the performance in terms of penetration capability, and range and along-track resolutions constrained by the challenges in the acquisition process, i.e. target dielectric properties, surface topography, and propagation through the ionosphere. Based on extensive simulations and performance assessment, the baseline is defined at a central frequency of 9 MHz with a bandwidth of 5 MHz, thereby allowing penetration of hundreds of meters through the crust with a range resolution around ~20 m depending on the target. Considering the ionosphere, the acquisitions are preferred on the night-side and are planned in three modes: (1) low density with track spacing of 50 km and lossy compression, covering at least 65% of the planet surface; (2) high density with track spacing of 10 km, covering relevant targets in specific region of interest; and (3) receiving only-mode for searching for possible lightning activity.

The presentation will address the science objectives and goals of SRS and the current status of the related scientific and technical activities.

Session 2: Science payloads and experiments – posters

Characterisation of the sensitivity to bias using a gain matrix formulation for the VeSUV/VenSpec-U instrument onboard ESA's EnVision mission

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Abstract

Selected in 2021 as the fifth class M mission of ESA's "Cosmic Vision" programme, EnVision is one the three next exploration mission of Venus, alongside NASA's VERITAS and DAVINCI. EnVision will bring a holistic approach, by studying the surface and subsurface, different layers of the atmosphere, past and present volcanic activity, as well as coupling processes. To that end, the payload will include a synthetic aperture radar for surface mapping (VenSAR, NASA), a subsurface radar sounder and a radioscience experiment to monitor gravimetric and atmospheric properties. Finally, the spectrometer suite VenSpec will investigate the surface and atmospheric compositions to analyse their relations with internal activity, using the thermal IR imager VenSpec-M and the high-resolution IR spectrometer VenSpec-H. The UV channel of the suite VenSpec-U, also called VeSUV, will focus on the atmosphere above the clouds, and aims more specifically at characterising the abundance and variability of sulphured gases such as SO and SO2, and the unidentified UV absorber. To do so, VeSUV will operate in pushbroom mode in the 190-380 nm range with an improved spectral resolution between 205 and 235 nm, and will observe the backscattered sunlight on the dayside of Venus at a spatial sampling ranging from 3 to 24 km. In order to characterise the instrument's performances, the sensitivity to bias is analysed using a gain matrix formulation. A perturbation is locally introduced on a synthetic spectrum and a fitting algorithm involving the same radiative transfer model is used to retrieve the atmospheric parameters, for several values of perturbation. As they are small, the assumption of a linear relation between the perturbation and the resulting error on the estimated parameters is made, their ratio corresponding to the matrix element. This method allows a conversion between the measured signal and the atmospheric parameters independently from the bias spectrum (e.g. straylight, calibration error, contamination during mission), as it is computed separately for each wavelength.

VenSpec-H: High-resolution IR spectrometer on ESA's EnVision mission to Venus

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Abstract

VenSpec-H uses 4 carefully selected near-infrared bands to perform absorption measurements in the Venus atmosphere. However, working in the infrared range imposes challenging thermal requirements on the instrument. To address this challenge, most of the (power consuming) electronics is detached from the optical bench. Additionally, the core of the instrument (the spectrometer section) is kept very cool to minimise the thermal background, and a cryocooled detector is used as the instrument's core.

This instrument builds on a number of high-tech subsystems, some of them identified as critical, and hence part of a TRL maturing strategy. The cold spectrometer section of the instrument contains the echelle grating at its centre, which receives light from a parabolic mirror and a freeform corrector plate combination. Spectral band selection is performed partly through a filter wheel mechanism, with stringent lifetime requirements, and a filter-slit-assembly, allowing to perform sequential measurements in the 4 spectral bands of interest. Design measures are taken to make VenSpec-H observations insensitive to polarization on one hand, but to exploit on the other hand, the polarization information contained in the light reflected from Venus.

While the development of VenSpec-H is challenging, especially from thermo-optical point of view, it is at the same time exciting to design, model, manufacture and test a scientific payload, to be embarked on board ESA's EnVision mission as part of the VenSepc suite [1], that will do unprecedented science.

References

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RT/ATOX-2: Miniaturized Real-Time in-situ monitoring of the degradation of materials due to ATOX etching – current development and experimentation

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Abstract

ATOX etching of exposed materials in LEO orbits and aerobraking operations can be significant for the exposed materials (for example for the Multi-layer Insulation, MLI). The Envision Assessment Study Report foresees densities up to 10^{17} O-atoms/m^3, which taking into account the 2000 atmospheric passes expected, lead to total oxygen fluences on the exposed spacecraft surfaces comparable to the case of LEO orbiting satellites.

In this abstract, we report the progress on a new miniaturized payload intended for monitoring in real time the etching of materials by ATOX. This sensor is the evolution of a first version developed at UPC for the 3Cat-1 Cubesat, launched in 2018, which used a MEMS resonator to detect changes in the mass of the deposited polymer (Pentacene), [1]. In this second version of the sensor, Quartz Crystal Microbalances (QCMs) that operate at 5MHz are used. One of the QCMs is used as a reference for temperature compensation; the other has the material of interest deposited on it. Both oscillators are fed into a digital circuit to monitor drifts in their resonant frequencies. The current version of the sensor implements two QCMs, their respective oscillator circuits, and a STM32 microcontroller for frequency measurement (COTS component). A second version using an FPGA is being developed for having multiple QCMs measured simultaneously. In order to achieve extreme miniaturization, the roadmap of a radiation-hardened-by-design mixed-signal ASIC is being developed in collaboration with the Microelectronics Institute of Seville (IMSE).

Preliminary experiments have been conducted with depositions of Aluminium by sputtering (thickness of 513 nm), Teflon by spin-coating (thickness of 2.48 μm) and resin (Microposit SPR 220 7.0) also by spin-coating (thickness of 6 μm). The average sensitivity of the QCMs in the Al and Teflon experiments has been 18.6 ng/Hz/cm2; and 23.6 ng/Hz/cm2 for resin. This last value suggests a certain non-uniformity of the resin deposition.

The temperature dependence, in the range 20°C to 60°C, has been ±16Hz for Aluminium, ±137Hz for Teflon and ±50Hz for the resin. In the Aluminium case, temperature compensation using a differential measurement with the reference QCM has reduced temperature dependence down to 1Hz. A first ATOX etching experiment has been made using an UVO cleaner on the QCM with resin, observing a frequency shift after etching of 546 Hz, indicating an average thickness reduction of 78 nm.

These preliminary results indicate that this type of sensors may provide real-time information on ATOX etching in space missions.

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Atmospheric Drag Effects on the Precise Orbit Determination of the EnVision Spacecraft

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Abstract

The atmospheric drag is the major non-conservative force that affects deep-space probes orbiting around Venus at low altitudes. This perturbation will significantly impact on the orbital evolution of the ESA's mission EnVision, which will be inserted into a 220×550 km orbit about Venus in its science phase. An accurate modeling of the atmospheric drag perturbations is required to accurately propagate the trajectory for the Precise Orbit Determination (POD) of the EnVision spacecraft. Semi-empirical predictions of the atmospheric density provided by general circulation models (GCM) are fundamental to reconstruct the orbit evolution. The Venus Global Reference Atmospheric Model (Venus-GRAM) and Venus Climate Database (VCD) have been developed to predict the properties of Venus' atmosphere, including vertical structure and dynamics, by using theoretical models refined through the analysis of data collected by previous missions. These two models rely on different assumptions, *e.g.*, dependence of atmospheric parameters on solar activity and on cloud albedo variability, yielding significantly different estimates of the atmospheric properties. We present here the numerical simulations of the EnVision POD during the science phase, based on a perturbative analysis of the atmospheric density. Although EnVision's orbit is not very low, the current uncertainties in the knowledge of the drag force model should nevertheless strongly affect the trajectory reconstruction and may impact the determination of the geophysical parameters (*e.g.*, gravity field coefficients and tidal Love number k_2). By accounting for mismodeling in the drag model consistently with the discrepancies between the predictions of the Venus-GRAM and VCD, we propose a POD method that allows us to compensate undesired errors in the determination of Venus' gravitational parameters.

EnVision VenSpec-M - key insights into the surface and surface-atmosphere interaction and volcanic activity of Venus

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Abstract

The VenSpec instrument suite on the EnVision mission consists of three channels: VenSpec-M, VenSpec-H, VenSpec-U, and the Central Control Unit (CCU).

VenSpec-M will provide near-global compositional data on rock types, weathering, and crustal evolution by mapping the Venus surface in five atmospheric windows. VenSpec-M will use the methodology pioneered by VIRTIS on Venus Express but with more and wider spectral bands, the NASA VERITAS VISAR and Envision VenSAR-derived DEMs, and EnVision's lower orbit compared to Venus Express to deliver near-global multichannel spectroscopy with wider spectral coverage and an order of magnitude improvement in sensitivity. It will obtain repeated imagery of surface thermal emission, constraining current rates of volcanic activity following earlier observations from Venus Express [1]. In combination with the observations provided by the identical VEM instrument on the NASA VERITAS mission VenSpec-M will provide more than a decade of monitoring for volcanic activity, as well as search for surface changes.

VenSpec-M is a pushbroom multispectral imaging system using a 14 bands filter array [2]. Those 14 bands fall in four categories depending on where the radiation is originating. The radiation for the six surface bands originates at the surface. Surface bands are used to determine rock types [3, 4] as well as monitor for the thermal signature of active volcanism. The radiation in the two water vapor bands originates in a layer close to the surface and is sensitive to the abundance of water vapor which may see changes due to volcanic exhalations, complementing the H20 and HDO measurements by VenSpec-H in the middle atmosphere [5]. In the three cloud bands, radiation originates at an atmospheric layer above the surface but below the clouds. Because the signal in the cloud bands has no surface or water vapor contributions, the measurements in these bands can be used to remove cloud-induced contrast variability from the other bands. Finally, the three background bands are sensitive in spectral regions where the atmosphere is opaque, thus allowing the removal of background signal on the detector. The high density of cloud particles results in multiple scattering of the radiation, reducing the spatial resolution to 50–100 km.

To correctly interpret VEM/VenSpec-M data and map the Venus surface composition an extensive laboratory calibration campaign is underway [6, 7, 8] as well as a series of field campaigns [8, 9, 10, 11].

[1] Müller et al, this meeting [2] Helbert, J., et al. (2019) 10.1117/12.2529248 [3] Dyar et al, this meeting [4] Helbert, J., et al. (2021), 10.1126/sciadv.aba9428 [5] Vandale et al., this meeting [6] Alemanno et al, this meeting

The VenSpec-U instrument on board EnVision

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Abstract

The VenSpec-U instrument is part of the EnVision mission as a core element whose main scientific objectives are to: *(1)* search for atmospheric effects of geological activity, in order to determine how much outgassing is occurring, and how the atmospheric chemistry is coupled with surface/subsurface geochemistry and weathering cycles; *(2)* study how mesospheric gas variations are linked to volcanism, in order to identify the causes of variability in the mesospheric sulphured gases (SO, SO_2); *(3)* study how cloud and particulate variability is linked to volcanism, in order to detect plumes of volcanic ash or sulphate clouds caused by volcanism, and to understand any link between the Venus sulphuric acid clouds and volcanism. VenSpec-U is consequently dedicated to the monitoring of the cloud top abundances of volcanic sulphured gases (SO, SO_2) as well as UV contrasts through spectral and spatial analysis of backscattered sunlight on the dayside of Venus.

Observations are based on a "pushbroom" observational strategy, and conducted in a strict nadir or near-nadir geometry thanks to a UV imaging spectrometer operating in the 190 – 380 nm spectral range. Spectral resolutions shall be better than 0.2 nm in the 205 – 235 nm range (typical SNR of 100 or above at 220 nm), and better than 2 nm in the 190 – 380 nm range (typical SNR of 200 or above at 220 nm). Spatial sampling shall range from 5 km to 24 km, depending on spectral resolution and orbiter altitude. The narrow-slit axis of the instrument contains the spectral information, whereas the long-slit axis contains the spatial information along the 20° field of view. The remaining spatial direction is provided through orbital scrolling.

The VenSpec-U instrument is based on a dual-channel architecture: the high spectral resolution (HR) and low spectral resolution (LR) channels are respectively operating in the 205-235 and 190-380 nm range. Each channel consists of an entrance baffle, an objective composed of two lenses and a stop diaphragm, and a spectrometer mainly composed of a slit, a short-pass filter to reject the wavelengths above the higher limit of the spectral band of interest and a spherical holographic grating. Each slit image is spectrally dispersed by its respective grating and formed on a shared CMOS back-side illuminated detector. The detector package includes a Peltier element used to cool down and regulate the detector allowing low dark current and stable behaviour. The detector is controlled such that the integration time and the binning scheme is adjusted independently (and simultaneously) for each channel giving high flexibility and providing parameters for the optimisation of each acquisition (SNR vs. spatial resolution vs. altitude vs. …). A wheel mechanism is implemented in order to protect the instrument against high fluxes and contamination, and to perform in-flight characterization and calibration. A UV source is used to perform in-flight flat-field monitoring as well as basic functional test and characterization of the detector.

Geodetic Contributions of the VenSAR Instrument for Inferring the Interior Structure of Venus

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Abstract

One of the science priorities of the EnVision mission is to constrain Venus' internal structure as well as to constrain the properties and thicknesses of Venus' crust, mantle, and core [1]. Measuring the moment of inertia and length-of-day variations of Venus provides critical geodetic constraints to understand the bulk interior structure of the planet. The polar moment of inertia of Venus is inversely proportional to the precession rate. Measuring the precession rate directly from orbit is challenging. For Magellan, spacecraft ephemeris errors dominated the measurement errors and for EnVision very similar challenges are expected. The precession rate itself depends on a number of geodetic parameters, namely the orbital mean motion, the spin rate, the second-degree gravity coefficient, the total mass of the planet, the radius, and the obliquity. To constrain the inertia tensor of Venus and hence to meet the EnVision objectives, the gravity field information must be complemented by measurements of the rotational state. Therefore, augmenting the gravity science solution with surface feature tracking and/or altimetry – abilities that VenSAR offers – can be critical in achieving EnVision science objectives.

VenSAR has the capability to make use of globally distributed VenSAR altimetry data and ground-track intersections (cross-over points) to create a dense geodetic net. These observations can be used in concert with gravity observations and SAR images to improve the a posteriori orbit determination, to solve for the rotation state of Venus including spin axis orientation and precession, and to allow the co-registration of other data products generated by the EnVision mission via improving the overall reference frame of Venus. The precise measurement of the rotation state allows us to infer constraints on the interior structure (e.g., by inferring the moment of inertia) as has been recently demonstrated by ground-based radar observations [2]. However, these recent measurements still provide a weak constraint on the internal density profile and core size, and improved measurements (reducing the uncertainty in the moment of inertia from currently 7% to about 4% and a measurement of the tidal Love number k_2) are needed to quantify the interior structure of Venus with precision [3].
As outlined in the yellow book, VenSAR will acquire a global network of altimetry mode tracks with a vertical resolution of 2.5 m, potentially providing a far better constraint than any previous dataset.

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The VenSpec-H instrument on board EnVision

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Abstract

VenSpec-H is part of the VenSpec suite [1], also including an IR mapper and a UV spectrometer [2]. The suite science objectives are to search for temporal variations in surface temperatures and tropospheric concentrations of volcanically emitted gases, indicative of volcanic eruptions; and to study surface-atmosphere interactions. Maintenance of the clouds requires a constant input of H_2O and SO_2. A large eruption would locally alter the composition by increasing abundances of H_2O, SO_2, and CO and perhaps decreasing the D/H ratio. Observations of changes in lower atmospheric SO_2, CO, and H_2O vapour levels, cloud level H_2SO_4 droplet concentration, and mesospheric SO_2, are therefore required to link specific volcanic events with past and ongoing observations of the variable and dynamic mesosphere, to understand both the importance of volatiles in volcanic activity on Venus and their effect on cloud maintenance and dynamics. VenSpec-H's main scientific objectives are (1) to better constrain the composition of the atmosphere both below and above the clouds to relate changes in the composition to changes on the surface or geological processes such as volcanism; (2) to investigate short and long-term trends in the composition to better grasp the climate evolution on Venus.

VenSpec-H is designed to measure H_2O, HDO, CO, OCS, and SO_2 on both the night and day side to contribute to this investigation. VenSpec-H is a nadir-pointing, high-resolution (R~8000) infrared spectrometer that will perform observations in different spectral windows between 1 and 2.5 μm. Spectra in these bands will be recorded sequentially with the help of a filter wheel and will allow the sounding of different layers in the Venusian atmosphere: close to the surface (1.17 μm), 15-30 km (1.7 μm), 30-40 km (2.4 μm) and above the clouds (1.38 & 2.4 μm). Two additional polarization filters will be used during dayside observations to better characterize the clouds' properties.

We will describe the scientific objectives of the instrument in detail and show how these relate to the requirements which have driven the design of the VenSpec-H instrument.

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Signature of Venus' atmosphere dynamics in its gravity field as seen by the EnVision radio-science experiment

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Abstract

The Venus atmosphere dynamics (mainly the thermal tides) are expected to generate temporal variations of the spherical harmonics coefficients of the gravity field of the planet (Bills et al., 2020). These time-varying effects was not detected in the latest solution of Venus' gravity field (Konopliv et al., 1996). In this study, we model these expected gravity variations and analyze whether it can be retrieved with the future tracking data of the EnVision spacecraft.

The atmospheric dynamics generate pressure variations that induce differential loading on the surface. Both pressure variations and loading contribute to the time-varying gravity field. The pressure variations are computed by accounting for the differences with respect to the mean value over the diurnal period of 117 Earth days. Our atmospheric modeling is based on the Venus Climate Database (Lebonnois et al., 2021). These pressure variations generate time-varying gravity field coefficients that can be computed for each degree assuming the values of the load Love numbers values (McCarthy and Petit, 2004; Petricca et al., 2022). These parameters are computed using a viscoelastic tidal deformation code, given an internal structure of the planet (Dumoulin et al., 2017; Tobie et al., 2019).

We perform simulations of the EnVision gravity experiment following the procedure described in details in Rosenblatt et al. (2021), thus using the GINS (Géodésie par Intégrations Numériques Simultanées) software developed by CNES (Marty et al., 2009). We simulate the EnVision tracking data with and without the contribution of the time-varying gravitational potential generated by the atmospheric dynamics. Then, we perform least-squares fit of the differences between both simulated tracking dataset in order to assess the capacity to retrieve the atmosphere-induced gravity variations. The goal of this study is in particular to assess our ability to correct the effect of the thermal tides on the estimation of the tidal potential Love number k_2 (real and imaginary part).

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Session 3: EnVision observation philosophy and strategy for Venus – oral talks

Studying Sedimentary Processes on Venus using Radar Polarimetry

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Abstract

The EnVision mission is focused on understanding the nature and current state of Venus' geological evolution, including the interactions between the surface and atmosphere. A key part of understanding Venus' evolution is the study of sedimentary processes and deposits present at the surface today. The sedimentary cycle is so important to our understanding of planetary evolution that these sources and sinks processes are captured in many of EnVision's top level science goals such as "Assessing Venus' surface modification process", "Understanding how the surface has evolved", "Understanding Venus' volcanic activity in the present era", "Assessing Venus' aeolian activity and mass wasting", and "Understanding the role of geological activity in Venus' climate evolution" [1]. In many ways, our knowledge of sediment production, transport and lithification is much better for Mars and the Moon than for Venus, partly because the Magellan radar could image through deposits and so the data do not always show evidence of sediments. EnVision's polarimetric radar VenSAR, combined with other EnVision data, has the potential to change how we think about the rock cycle on Venus.

Radar polarimetry provides a method to determine and map the surface structure beyond what can be achieved with single polarization data. It provides context and improved science interpretation to radar images. Ratios of polarimetric data products, as well as decompositions, can be used to identify types of scattering, assess surface roughness, and detect geologic units that could be low density mantling deposits. Prior radar polarimetry from Arecibo Observatory revealed that surface sediments are more common than was thought based on Magellan data, and are often associated with volcanic summits, crater ejecta, and aeolian deposits [e.g., 2]. EnVision's VenSAR polarimetry data will provide dramatically improved maps of surface cover in these areas of interest, which will help to assess the boundaries of mantling deposits and identify source regions of sedimentary material. VenSAR polarimetry, with its tens-of-meter scale spatial resolution, will also be able to detect mantling deposits surrounding debris flows, and look for evidence of erosion and sediment deposition in the tessera regions at small scales. In addition, VenSAR's higher resolution single-polarization mode will be able to look for evidence of layered deposits that could indicate sedimentary rocks. Combining the VenSAR images with other data products such as VenSAR radiometry and stereo, and SRS reflectivity and sounding, will provide a new understanding of how the surface of Venus is evolving today.

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Meteoroid Airburst Scars on Venus

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Abstract

More than 2% of Venus' surface is scarred by large, circular radar features associated with meteoroid airbursts. These deposits occur coincident with impact craters ("dark haloes", N ~ 350) and as standalone features ("splotches", N ~ 300). Airburst scars are thought to form when meteoroids breakup in the lower atmosphere, rapidly decelerate, and dump kinetic energy into shockwaves powerful enough to alter surface morphology [1]. On Earth, meteoroid airbursts can flatten large sections of forest or cause damage to human infrastructure—examples include the Tunguska event and Chelyabinsk airburst, respectively. The thicker atmosphere of Venus allows for significantly more energetic airbursts. Past studies posit that Venus airburst deposits occur when shockwaves pulverize bedrock into fine sediment, resulting in ephemeral, decimetres-thick scars that are visible in past missions' radar imagery datasets [2-4]. Notably, past airburst models have not been able to produce all the characteristics of airburst scars, and some additional formation mechanism may be needed.

Despite their prominence on Venus, airburst scars are relatively under-studied and poorly understood. We have started a new survey of candidate airburst scars—and new models of their production and destruction. Our ultimate goal is to use airburst scars (like impact craters) to test models of global volcanic resurfacing. So far, we confirmed that splotches (unlike impact craters) are spatially non-random. We found a dearth of splotches in the highlands, including tesserae. Some process must inhibit formation, preservation, or observability of airburst scars on rough terrain. However, splotches are even more clustered than this geographic bias can explain. Resurfacing [1] or bolide chains [4] may cause further clustering. Airburst deposits erode more readily than craters and display several modification states—likely from a combination of aeolian erosion, sedimentary deposition, and volcano-tectonic activity. Airburst scars can be divided into morphologic groups, forming concentric patterns of radar-dark and radar-bright deposits at radial distances. The cause of these morphologic groups is unknown, but may be related to terrain properties, airburst altitude, bolide velocity/composition, or some other factor [3]. Overall, Venus has the largest, most well-preserved inventory of airburst deposits in the solar system. Meteoroid airbursts occur on any world with an atmosphere (e.g., Earth, Mars and Titan); understanding the nature of meteoroid-atmosphere-surface interactions here will benefit the study of this geologic process for several other planetary bodies.

The EnVision mission represents an unprecedented opportunity to study airburst features. The VenSAR and SRS instruments together will measure many surface properties at airburst deposits, providing strong constraints on any models of their formation and erosional states. This will help achieve the larger mission goal of understanding Venus geochronology and geodynamics. We will present ideas about a targeting strategy for EnVision that will increase observational efficiency and coverage for diverse airburst morphologies and help maximize science returns for the mission.

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EnVision VenSAR Stereo Topography as a Constraint on Tectonic Structure and Evolution on Venus

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Abstract

The EnVision VenSAR radar will measure the topography of Venus in two ways, using both stereo imaging and globally distributed altimetry profiles. Stereo imaging will provide the highest horizontal resolution data, with digital elevation models from image pairs with look angle differences of 5 degrees expected to have 300 m horizontal resolution and 30-50 m vertical resolution for ~28% of the Venus surface [1]. This data will be complementary to interferometric topography (InSAR) for Venus that is expected to be obtained by the VERITAS mission.

Quantitative modelling of faulting and folding can be used to place important constraints on the types and magnitude of tectonic deformation on Venus. Two recent studies using the Magellan stereo topography model [2] provide useful examples of the types of science that VenSAR expects to achieve. Resor et al. [3] measured folding in tessera terrain in Tellus Regio. Based on the dominant fold wavelengths and amplitudes, they determined the total strain in this region and constrained the lithospheric thickness and heat flow at the time of tessera emplacement. Moruzzi et al. [4] modelled thrust faulting in the Vedma Dorsa ridge belt. Their results constrained the total fault displacement, maximum depth of faulting, and fault dip. Their results also suggested there are components of both blind faulting and listric faulting in this region. These two studies serve as examples of the types of modelling that we expect to be able to do with higher resolution VenSAR stereo topography.

EnVision's globally distributed stereo topography data will include type examples of all major types of tectonic terrain. This will permit quantitative modelling of lithospheric folding and faulting, including determining the total extension or shortening. These models will also constrain lithospheric thickness and rheology, which in turn will provide estimates of lithospheric heat flow as a function of time and space. Comparisons of the types of deformation that occurred on Venus with similar terrain types on Earth (e.g., mountain belts or rift systems) will help to determine the type(s) of mantle convective regimes that have occurred during the geologic history of Venus (e.g., mobile lid, stagnant lid, plutonic-squishy lid, transitions between these modes, or something else). The temporal record of heat flux will serve to test models of convective evolution [e.g., 5], which are in turn possibly linked to changes in atmospheric structure and climate over time [6].

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On the Distribution of Seismicity on Venus

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Abstract

Episodic resurfacing, stagnant lid models, and the distribution of impact craters on Venus has previously led to an assumption of intraplate levels of activity on Venus which combined with an inferred thin seismogenic thickness because of its high surface temperature, implies a very low level of seismic activity, <50 Venusquakes of M≥5. Yet Venus is one of the most fractured planets in the Solar System, and recent research suggests a far more active planet based on new observations and improved numerical models. Even with its thin seismogenic zone, our estimates for this more active Venus range between 200 and 1100 Venusquakes of M≥5, and between 30 and 130 Venusquakes of M≥6, and more than 100 Venusquakes of M≥3 every 24 hours, dramatically enhancing the possibility for their detection. But where are these Venusquakes likely to occur?

In the oceans, seismicity is mostly concentrated into narrow regions close to plate boundaries, with the greatest number and largest magnitudes associated with subduction zones, where the seismogenic zone is at its deepest. The distribution of seismicity in the continents is more complex but is broadest and most severe in active orogenic belts. Because basalt at Venus conditions is rheologically similar to granite under terrestrial conditions, seismicity on Venus may follow a similar pattern, with the important caveat of a thinner seismogenic zone on Venus. Evidence for crustal block (campus) deformation suggests that this pattern of seismicity might widely distributed on Venus away from the lowest elevation plains and that seismicity might be recorded almost anywhere on the planet.

However, two other situations are worth considering. Recent evidence suggests that approximately a third of coronae have morphologies consistent with active subduction at their annuli. Subduction implies both a thicker seismogenic zone, because of the relatively cold sinking plate, and higher magnitude quakes. These morphologically 'subducting' corona may offer the best opportunity for detecting seismicity on Venus. The other situation worth considering are the tesserae plateaux. Many of these complex, highly deformed crustal blocks apparently have active margins and may even be drifting across the surface. While they may possibly have a weaker (plagioclase) rheology, they appear to be significantly thicker and colder than other regions of Venus and may therefore have a thick seismogenic zone.

Taking all these factors into consideration, perhaps the most promising area to target for seismicity is in the region including Thetis Regio and Artemis Corona, with the opportunity to capture seismicity associated with subduction, tesserae plateaux, and campus block tectonics.

Estimates on the expected annual seismicity of Venus

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Abstract

There is a growing consensus that Venus is seismically active, although its level of seismicity could be very different from that of Earth due to the lack of plate tectonics. Here, we estimate upper and lower bounds on the expected annual seismicity of Venus by scaling the seismicity of the Earth. We consider different scaling factors for different tectonic settings and account for the lower seismogenic zone thickness of Venus. Preliminary calculations show that 4 - 40 venusquakes $\geq M_w$ 5 per year are expected for an inactive Venus, where the global seismic rate is similar to that of continental intraplate seismicity on Earth. For the active Venus scenarios, we assume that the coronae, ridges, and rifts of Venus are seismically active. This results in preliminary estimates of 18 - 207 venusquakes $\geq M_w$ 5 annually as a lower bound and 90 - 1099 venusquakes $\geq M_w$ 5 as an upper bound for an active Venus.

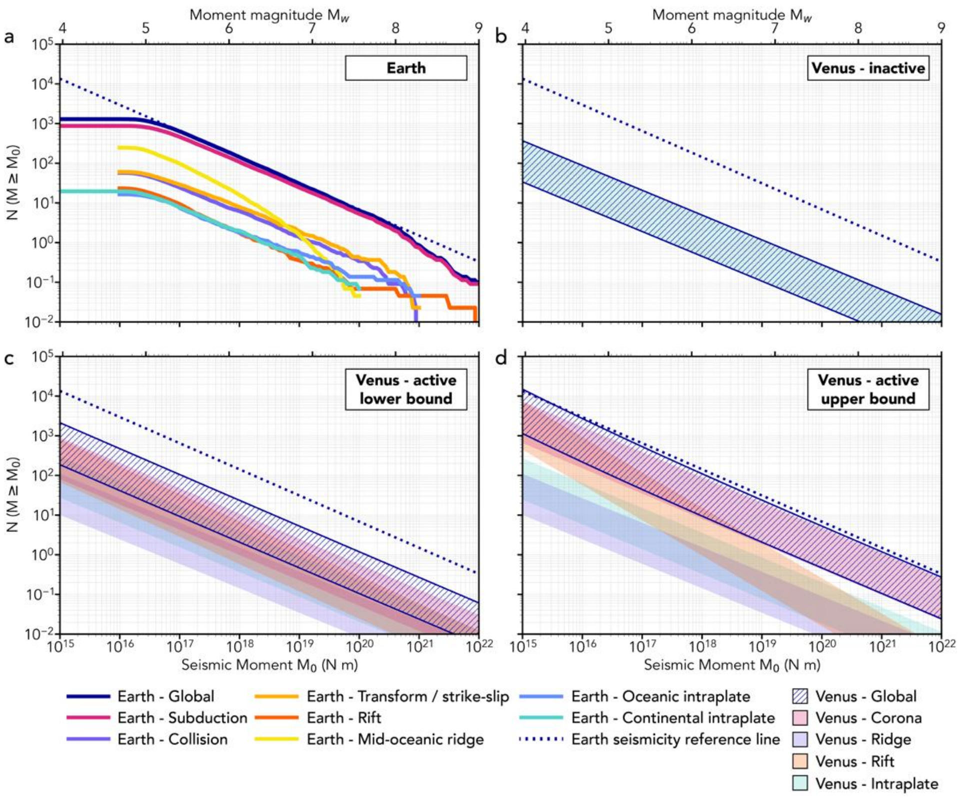

Figure 1 (a) Annual earthquake size-frequency distribution for Earth based on the CMT catalogue and split into different tectonic settings. (b-d) Ranges of potential quake size-frequency distributions on Venus for (b) an inactive Venus with purely background seismicity analogous to Earth's intraplate seismicity; (c) a lower bound on an active Venus; and (d) an upper bound on an active Venus. The dark blue range shows the global, accumulated annual seismicity that combines the seismicity of the different individual tectonic settings. Note that because of the log-log scale, the global estimate and the seismicity range of the highest individual tectonic setting are closely-spaced. Dotted dark blue line indicates the reference Earth seismicity line, which corresponds to the slope of the global seismicity on Earth.

Venus shield volcano flow apron margins: Primary targets for joint analysis of EnVision VenSAR and SRS datasets.

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Abstract

Access to high-resolution topography, imaging, and sounding datasets opens up opportunities to address long-dormant issues in the structure and evolution of large shield volcanoes on Venus. Based on Magellan imaging and topography, these were characterized as comprising topographically prominent central edifices with encompassing aprons of edifice-radial, generally radar-bright lava flows over exceedingly low slopes – more than 140 such edifices with flow apron diameters > 100 km have been identified [1]. Models of the flexural response of the lithosphere to the load of the edifice + apron volcanic complex predict a flanking topographic bulge (the "flexural arch") that would tend to contain the outermost flexural moat-filling volcanic flows [1]. One might expect that radially directed flows would eventually encounter the arch as a barrier and be diverted sideways into circumferential orientations, unambiguously detecting the arch and perhaps allowing the thickness of the elastic lithosphere T_e to be estimated if sufficient moat-edge topography is preserved. However, this kind of distal circumferential flow is rarely seen, the two most prominent exceptions being Tepev Mons and Tuulikki Mons. Further, clear-cut detections of continuous annular topographic arches with the superposed circumferential graben predicted by stress models are lacking, and in any event the nearly full moats encircling Venus volcanoes obscure nearly the entire topographic signature of the pre-existing lithosphere that would be used to estimate T_e.

Data from EnVision instruments VenSAR (S-band Synthetic Aperture Radar) and Subsurface Radar Sounder (SRS) can provide new ways to unravel these issues [2]. VenSAR datasets would provide order-of-magnitude resolution improvements over existing Magellan datasets. VenSAR imaging at Regional (30 m) and Targeted (10 m) scales [2] would allow improved identification of volcanic edifice unit boundaries. New topography datasets from VenSAR Stereo SAR [2] or the VERITAS mission, also providing order of magnitude resolution gains (300 m or better), would vastly improve the ability to identify subtle flexural arch topography that would be otherwise obscured amid natural regional variations. But the game-changer here is the subsurface interface detections from SRS, which is designed to sound the top kilometer of the interior [2]. Material property contrasts between volcanic edifices and pre-existing regional units (likely volcanic "plains") may be large just by the nature of differing magma compositions, pathways, and supply rates. Further, such differences would likely grow with the time elapsed between plains and edifice formation due to effects such as weathering and impacts. This detection would therefore work best for the combination of youngest volcanoes & oldest plains that gives the greatest age differences, potentially yielding a complementary means to analyze the evolution of youngest (potentially active) volcanoes. Synthetic stratigraphic reconstructions of volcano-lithosphere boundaries at moat margins [1] show that the segment of this boundary contained in the uppermost kilometer of the crust is of sufficient extent to be diagnostic of lithosphere thickness.

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Imdr Regio: the geology of a possible active hot spot on Venus and a target for future exploration by the ESA EnVision mission.

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Abstract

With Venus being the focus of future new missions like ESA's EnVision, we need to look for target sites for future investigations on Venus. The different instruments will help to study the planet in unprecedented detail. In particular, the VenSAR instrument will map 20% of the surface of Venus at a resolution of 5 to 10 meters/pixel, making it crucial to carefully select what areas of Venus deserve to be targeted for such a high-resolution mapping. We propose here Imdr Regio as a good candidate location for combined high resolution SAR mapping and for study with the rest of the mission instruments (e.g., Subsurface Radar Sounder).

Imdr Regio is a large topographic rise that extends approximately from 35ºS-50ºS and 195ºE-225ºE between the volcanic plains of Helen, Nsomeka and Wawalag Planitiae. Imdr Regio is classified as a volcano-dominated topographic rise with a minimum-maximum diameter of 1200-1400 km and a swell height of 1.6 km. The southeast of Imdr Regio is dominated by Idunn Mons (46.5ºS/214.5ºE). Studies using the 1 μm (derived) surface emissivity from the Venus Express mission of the volcanic flows surrounding Idunn Mons suggest that high emissivity values in the volcano flanks are related to relatively unweathered basaltic rock and therefore indicative of a recent or even ongoing volcanic activity.

We have carried out geologic mapping in the area to constrain volcanic and tectonic structures, and the geologic history of the large topographic rise. This geologic mapping reveals that different styles of volcanism are present across Imdr Regio and that this volcanic activity takes place across the hot spot concurrently with the formation of a rift in the area.

The first stages on the evolution of this large volcano are characterized by the formation of a radial fracture system and contemporaneous large sheet flows. These large sheet flows are locally difficult to distinguish from regional plains and are also deformed by regional N-trending wrinkle ridges.

After this initial phase, multiple overlapping digitate flow units form the flanks and summit of the volcano and are contemporaneous with NW-SE trending fractures and graben of Olapa Chasma, a rift system that cross the topographic rise.

To the northwest another large volcano also presents a system of radial fractures but lacks clear large sheet flows. Numerous pit chains are associated to fractures and graben, suggesting that transport of magma under the surface is important.

The geologic history based on the mapping suggests that activity in Imdr Regio started with the emplacement of a plume/diapir in the southeast, which resulted in the formation of a radial dyke system and the emplacement of large sheet flows in Idunn Mons. The presence of other large volcanoes to the northwest suggests the presence of another magmatic source (plume or diapir). After this initial stage, volcanism continues in Idunn Mons and activity in the topographic rise is strongly related to the formation of Olapa Chasma. Rift-related volcanic flows postdate these other volcanoes and are contemporaneous with the late activity in Idunn Mons. Monogenetic volcanism is present in the rift and in all the units that are in the area.

Looking for Change on Venus' Surface with Radar

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Abstract

The selection of two Venus missions with Synthetic Aperture Radars coupled with existing Magellan imagery of the surface offers an unprecedented opportunity to look for changes on the surface of Venus from a variety of geophysical processes at multiple time scales ranging from decades to months. Detection of surface change is integral to understanding the processes presently modifying the surface of Venus and to provide a window as to how these processes have contributed to the evolution of Venus to its present state.

The most comprehensive mapping of the surface of Venus was done by the Magellan mission in the early 1990s. Magellan employed an S-band SAR, altimeter and radiometer to make nearly global observations of the surface of Venus. SAR imagery was collected with spatial resolution between 100 and 300 m and the altimeter made topographic measurements with a spatial resolution of 15-20 km with a vertical accuracy of ~100 m. SAR observations were made over 3 cycles with roughly 40% of the planet being observed 2 or more times. VERITAS will map the surface of Venus with X-band radar having 30 m resolution globally and will map > 20% with 15 m resolution imagery starting in the early 2030s. Nearly the entire surface will be mapped 2 or more times during the 4 cycles of the primary mission. VERITAS will also map the topography of Venus with 250 m spatial resolution and 5 m vertical accuracy. EnVision, operating in the mid to late 2030s will map 30% of the surface with 30 m S-band imagery and 1-2% with 10 m imagery. About 6% of the surface will be acquired in a dual polarization (HH, HV) mode. Between 20-25% of the surface will be acquired with same incidence angle imagery.

The combined data of the three mission enables repeat observations of the surface with timescales ranging from 4 months to 45 years. The finer resolution imagery obtained by the VERITAS and EnVision radars will improve the chances of detecting changes on the surface. Because these data are collected at different wavelengths, resolutions, incidence and aspect angles, avoiding false detection of surface change requires particular care. This paper will discuss some of the opportunities for detecting surface change and techniques for avoiding such false detections. We will illustrate some of these techniques with a recent detection of volcanic change with Magellan Cycle 1 and 2 images. Differential interferometry will provide the most sensitive measure of surface change with observations acquired during the VERITAS mission that are illustrated for a range of Mogi sources.

A portion of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The information presented about VERITAS and EnVision is pre-decisional and is provided for planning and discussion purposes only.

Holistic change detection of Venus' surface features

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Abstract

We expect that in the next decade or so Venus will be proven to be the second most geologically active planet in our solar system. Demonstrating that activity is one of EnVision's top level science goals [1], and it has the capability to detect changes to the planet's surface in a number of ways. Imaging with consistent geometry and scale, repeated imagery at 30 m spatial resolution, and imaging at high resolution (10 m) from VenSAR will play vital roles in identifying both new features and those which have changed with respect to Magellan. Such changes may include new lava flows, new and smaller volcanic edifices, and new and perhaps smaller landslides than those identified in Magellan's imagery. Better topographic data will play a vital role in understanding relationships between image surface features and their likely subsurface structure. Thermal emissivity imaging from VenSpec-M at high temporal frequency will add important complimentary evidence through the detection of new eruptive phenomena during the course of the mission. Resolving such 'hotspots' should provide the trigger for tasking targeted high resolution SAR imaging at a particular location. VenSAR's dual polarisation capability will also add surface material context to any existing or newly detected mass movements, as well as across young volcanic materials or impact ejecta debris.

The only way to detect very small scale changes, such as those caused by regional scale crustal or block motions [2], inflation or subsidence of thermally anomalous volcanic edifices [3, 4], or displacement on small faults, fractures and tectonic boundaries, is using repeat-pass SAR interferometry. It is anticipated that there will be number of opportunities during the EnVision mission, when the critical baseline distances between orbital passes will be suitable to measure the phase difference between SAR observations separated in time. If suitable SAR observations can be made in such a way as to preserve the interferometric coherence between them, then not only will deformation measurements be achievable but centimetre-scale surface changes will also be detectable using interferometric coherence loss. Coherence, as a measure of the local spatial correlation between observations, allows the detection of cumulative changes to random surface scatterers on the ground which may be caused by a variety of processes including material erosion, transport and deposition.

These observations should together enable signs of current geological activity to be captured and characterised by EnVision's suite of complementary instruments, with respect to past imagery and during the course of the mission. To better understand the changes that will be detectable, some constraint on the likely rates and scales is needed from Earth analogues and through simulation of EnVision's image products.

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Assessing Rates of Volcanic and Tectonic Activity on Venus with EnVision

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Abstract

Establishing the rates and types of current geological activity on Venus is one of the principal objectives of the EnVision mission [1]. And there are plenty of reasons to expect active geological processes on the planet, given that Venus is almost the same size and about 80% the mass of Earth. Moreover, the planet's anomalous paucity of impact craters [2], plethora of volcanic and tectonic landforms [3,4], and global but photochemically unstable cloud layers [5] all point to major magmatic and geodynamic activity over the last several hundred million years—and perhaps even to the present.

Recent studies have provided further impetus for assessing rates of geological activity on Venus. Extrapolations of the (incomplete) eruptive record on Earth to Venus suggest that there may be as many as several dozen new or ongoing volcanic events on the second planet [6]. Considering the likely severely undercounted number of submarine eruptions on Earth [7], together with new mapping of discrete edifices on Venus indicating *many* thousands of small volcanoes there [8], it may be that Venus will be found to be at least as volcanically active as Earth's terrestrial domain.

Tectonic work has shown that, in some parts of the planet's lowlands, the upper, brittle lithosphere is fragmented into discrete crustal blocks, with strains along their margins indicative of lateral rotations and translations akin to jostling pack ice [9]. This fragmentation is observed in stratigraphically young plains, implying that at least some lateral motion has taken place geologically recently. Similarly, there is structural evidence that some portions of tesserae have been formed by the incorporation via crustal shortening of stratigraphically young plains, with strain axes consistent with modern-day deep mantle flow directions [10].

High-resolution VenSAR radar data in select regions of interest, contextual spectral and stratigraphic measurements by the VenSpec suite and the SRS instruments, and—where possible—repeat-pass interferometry will be powerfully enabling in understanding whether, and to what extent, Venus is volcanically and tectonically active.

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Quantifying volcanism on Venus with VenSAR: Comparison with Earth

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Abstract

While previous Venus missions have provided hints of surface volcanism on Venus, EnVision and other new missions will better quantify volcanism by comparing repeat pass imaging among missions (including data from Magellan in the 1990's) spanning months to decades [1]. Improving estimates of the current volcanic flux on Venus (currently estimated to be between 0.01-10 km^3/yr; [2-3]) could constrain models of the Venusian interior.

There are a variety of ways that EnVision will measure recent volcanic activity, including repeat pass interferometric phase and coherence change, radiometry, topographic and radar amplitude change, and others -- each with a different sensitivity to volcanic activity [4-5]. One concern with comparing imagery across decades is that many large eruptions may not be resolvable in the 100-300 m/pixel Magellan imagery, and so could lead to under-estimates of eruptive flux. Here, we explore to what extent terrestrial volcanic activity can inform detection thresholds of Venusian volcanic activity from the different EnVision sensors, particularly VenSAR, a Synthetic Aperture Radar. We build on recent estimates of Venusian eruptive frequency extrapolated from Earth over the last 40 years [6] with a new synthesis of the spatial and temporal characteristics of these eruptions in different geodynamic settings [7] to bound detectability from satellites at Venus. Further, modern terrestrial SAR data from dozens of satellites span different radar bands and spatial resolutions from less than 1 meter/pixel to dozens or even hundreds of meters/pixel [8] and can help bound the spatial and temporal characteristics of expected intrusive, explosive, and effusive magmatic and volcanic activity on Venus that can be measured by EnVision and other sensors.

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The value of a semi-random InSAR campaign with EnVision

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Abstract

Current big-picture geodynamic scenarios to explain the existing state of knowledge of Venus produce widely varying accounts of the current expected level of tectonic and volcanic activity, the nature of that activity, and where it is occurring. Some of the endmember ideas under discussion include: Venus is at a nadir of geologic activity with limited volcanic and tectonic activity presently occurring only in association with the major rift systems and where they interact at major volcanic swells (e.g., Basilevsky and Head, 2002); Venus has volcanic and tectonic activity everywhere, and it varies in nature but the end product is a surface comparable to Earth's oceanic crust in age (e.g., Herrick and Rumpf, 2011); the planet's surface is a set of jostling microplates, moving and rotating a bit but generally not subducting (e.g., Byrne et al., 2021). These hypotheses are not all mutually exclusive. Their combined effect is to suggest that nearly anywhere on the planet could conceivably have a new volcanic flow or have the surface moving in a way detectable by InSAR.

Because VenSAR will return the full SAR waveform data, an InSAR (interferometric synthetic aperture radar) pair can always be collected if the viewing conditions are acceptable when EnVision passes over a previously imaged sight. Unfortunately, the planned varying orbital altitude of EnVision from imaging cycle to cycle (~20 km change each cycle, with a "cycle" indicating a Venus sidereal day) means that the cross-track offset will be ~0-5 km when only a narrow range of cross-track offsets will yield acceptable geometry for InSAR imaging. The offset will slowly progress from minimum to maximum, but in a way that knowing the few percent of times when the swaths will be within an acceptable perpendicular baseline of a few hundred meters will be predictable in advance by something on the order of days to weeks.

Geologic mapping, time lapse observations from Magellan to Envision, non-InSAR repeat imaging during EnVision, thermal anomalies in IR and microwave emissivity, and other methods will certainly identify active and most-likely-active areas on the planet that will present critical targets of opportunity for times when an InSAR imaging opportunity fortuitously occurs over them. However, the diversity of geodynamic scenarios that have been hypothesized suggests that taking every opportunity to collect an InSAR pair to look for ongoing movement/deformation in a way that samples the EnVision ROIs as broadly as possible will place valuable constraints on these proposed geodynamic scenarios and might yield some exciting surprises.

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Detecting recent volcanism on Venus using VenSAR radiometry

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Abstract

Venus is thought to be volcanically active at geologic timescales based on evidence from prior spacecraft observations. However, the modern rate and spatial distribution of active volcanism on the planet remain unknown. Addressing the question of whether Venus is volcanically active, and placing constraints on observable levels of activity, is critical for understanding the coupled surface-interior-atmosphere evolution of Venus, and would also yield broader insights into how volcanic processes shape rocky bodies across the solar system.

One of the science objectives of the EnVision mission is understanding Venus's volcanic activity in the present era using complementary observations techniques [1]. Repeat, targeted imaging of the surface by VenSAR, at similar wavelengths and observation geometry to Magellan, will allow for detecting volcanic modification of the surface over a 40-year baseline, and also during the span of EnVision's science operations. At global scales, VenSpec-M and VenSAR (in the radiometer mode) have the capability to observe elevated thermal emission at near-infrared (NIR) and microwave wavelengths associated with ongoing and/or recent volcanism. VenSpec-M will search for surface thermal anomalies, complemented by VenSAR radiometry which will probe the shallow subsurface for elevated temperatures at depth. VenSAR radiometry, therefore, is particularly suited for detecting months-old lava flows that will still retain higher temperatures in the interior, even after the surface has equilibrated to the ambient temperature on Venus [2,3].

Characterizing current rates of volcanism on Venus is dependent on successfully relating any elevated surface thermal flux and brightness temperature measured by VenSpec-M and VenSAR radiometry, respectively, to physical parameters such as lava flow temperature, age, morphometry, etc. This motivates our study into understanding how volcanic flows behave on the surface of Venus and what their expected NIR and microwave emission would be. We will discuss how established models of lava flow emplacement and cooling on Earth and Io can be adapted to 1) characterize active and recent lava flows on Venus, 2) determine their temperature profile and spatial extent, and 3) estimate surface thermal and subsurface radiothermal emission. This work will provide a first order understanding of the size and thermal characteristics of eruptions on Venus that can be detected by EnVision at global scales, and also provide a framework for inverting observations of NIR and microwave emission to physical characteristics related to volcanic eruptions on Venus.

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Investigating Venus' geological History and Activity with VenSAR radiometry

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Abstract

The ultimate goal of the EnVision mission is to understand why, though very similar in terms of size, composition and distance to the Sun, the Earth and Venus have evolved so differently, the former being habitable while the latter seems to have experienced a dramatic climate change [1]. In this task, the VenSAR instrument will be key as it will provide insights into Venus geological history (How have the surface and interior of Venus evolved?) and activity (How geologically active is Venus?), two of EnVision's highest-level science themes.

VenSAR will operate either (i) as a SAR (Synthetic Aperture Radar) to image the surface with a standard resolution of 30 m, (ii) as an altimeter to measure altitude variations or (iii) as a (passive) radiometer recording the microwave thermal emission from Venus' surface. Its strategy of observations will combine targeted (SAR, polarimetry) and global-scale (altimetry, radiometry) observations. In its radiometry mode, as a baseline, it will operate in a nadir or near-nadir viewing geometry but opportunistic off-nadir polarized measurements will be performed in specific regions of interest.

In this presentation, we will show how the VenSAR radiometry dataset, in synergy with other EnVision observations (especially from VenSAR active operating modes and VenSpec-M), will address EnVision key science objectives, providing clues on (i) Venus' surface properties (composition, density) through, in particular, the measurement of its surface dielectric constant [2], (ii) surface modification mechanisms, especially in regions of high elevation that possess an unexpected low microwave emissivity [3] and (iii) possible current volcanic activity on the planet with the search of hot spots in the near-subsurface [4].

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On the determination of Venus' gravity field by EnVision

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Abstract

The gravity field of planets is determined using the perturbations method where an *a priori* trajectory is refined by applying a least-squares adjustment filter to the spacecraft radio-tracking data. These measurements are the Doppler shifts of the carrier frequency of a radio-link established between the spacecraft and deep-space tracking stations on Earth. This approach has been successfully used for example to compute the gravity field of Mars with an almost uniform spatial resolution of about 110 km using up to 20 years of daily tracking data from spacecraft with low-altitude and near-circular orbits (e.g., Konopliv et al., 2016; Genova et al., 2016). The current resolution of Venus' gravity field is however much worse with a heterogenous resolution between 475 km and 170 km (Konopliv et al., 1999), since tracking data is available for only two spacecraft (Pioneer Venus Orbiter and Magellan) which had shorter mission durations, higher elliptical orbits and noisier Doppler data compared to that of Martian spacecraft. Recently, three new missions have been selected to target Venus. Two of them, NASA-VERITAS and ESA-EnVision, will provide opportunities for improving the current solution of Venus' gravity field. Here, we focus on the EnVision gravity experiment which is part of the radio-science experiment (Dumoulin et al., 2022).

The spatial resolution of a gravity field depends on the altitude of the spacecraft orbit: the lower the altitude, the higher the spatial resolution, provided that the spacecraft flies over the entire sphere while it is tracked from Earth. The three Venusian days (or cycles) provided by Magellan tracking data were not long enough to reach this requirement. The tracking data of the Envision science phase will be acquired over six cycles allowing the entire sphere of the planet to be covered. EnVision's elliptical orbit (between 220 and 515 km altitude) will not yield a uniform spatial resolution of the gravity field, but high resolution (up to 145 km) can be achieved locally through the drift in latitude of the orbit pericenter over the mission duration.

The variability of the Doppler data noise is accounted for in our simulations by including the troposphere, ionosphere and solar plasma effects. The dispersive media contribution is partially calibrated by the dual-frequency on the downlink of the EnVision spacecraft. The resolution of the gravity field is also affected by the limited knowledge of the non-gravitational forces (e.g., atmospheric drag, solar radiation pressure).

To take all these effects into account in the gravity experiment simulations, we need to use dedicated geodesy software. Here we have used the GINS software developed by CNES (Marty et al., 2009; Rosenblatt et al., 2021) as well as the GEODYN II (Pavlis et al., 2013) and MONTE (Evans et al., 2018) software developed by NASA. All three provide similar results, validating the expected improvement of the gravity field resolution by EnVision. Limitations of the expected gravity resolution (e.g., mission duration, Doppler noise level, knowledge of non-gravitational forces, …) will also be discussed.

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EnVision aerobraking: unique opportunity to infer in-situ density, temperature, waves in the Venus upper atmosphere

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EnVision will be launched in November 2031 with an orbit insertion around mid-2032. This will be followed by circularization through aerobraking over a period of about 16 months to achieve a low nearly-polar Venus orbit, with altitudes varying from 220 to 540 km (the nominal science orbit) [1]. Aerobraking consists of a sequence of thousands of orbital revolutions during which the spacecraft dips into the upper atmosphere around the pericenter, resulting in a progressive reduction of the apocentre altitude. This phase offers a unique opportunity to obtain valuable scientific information on the uppermost layer of the Venus atmosphere, in addition to the nominal science objectives.

Previous experiments during aerobraking campaigns on both Venus and Mars were very successful. For example, Venus Express (VEx) Atmospheric Drag Experiments (VExADE) allowed in-situ measurements of total mass density and detection of atmospheric waves in the region between 130-180 km altitude using 3 different techniques: POD (Precise Orbit Determination) [2], Aerobraking [3] and Torque [4]. Before VEx, Magellan density measurements on Venus had been obtained via aerobraking in the region from 135-150 km, and PVO data at low latitudes with POD and in-situ mass spectrometer measurements. On Mars, five different spacecraft employed aerobraking. This has allowed the in-situ determination of the thermospheric densities and temperatures, revealing for example the presence of a warm area in the winter pole [5], the effects of small-scale gravity waves [6], the prominent role of thermal tides in the thermosphere [7], or the estimation of thermospheric winds [8]. In addition to density and wave measurements in the atmosphere, high resolution local gravity field determination is possible. For this, frequent tracking of the spacecraft is needed close to the pericenter (e.g., with low gain antennas), which should be at the lowest altitude that is safely possible. Furthermore, radio occultation measurements can be obtained during the aerobraking phase to retrieve ionospheric electron density and neutral atmospheric temperature profiles, whenever the spacecraft is occulted by Venus with respect to the line-of-sight of the ground tracking stations.

In this study, we will present an overview of the possible bonus science during EnVision's aerobraking phase, depending on the final strategy, pericenter altitude and location, S/C specifications. State-of-the art models (e.g. Venus-PCM [9], VTGCM[10]) and database (e.g. VCD [9]) will be used to provide inputs to tools previously used during VExADE depending on different scenarios (e.g. EUV flux, day-nigth variations, location of the pericenter)

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Simulated Retrievals of H_2SO_4 and SO_2 from EnVision RSE Measurements

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Abstract

In addition to profiling Venus' atmospheric and ionospheric structure via Doppler shift measurements, EnVision's Radio Science Experiment (RSE) will also measure the abundances of H_2SO_4 and SO_2 via the radio link attenuation during occultation. While many profiles of H_2SO_4 vapor have been determined from prior X band radio occultations, the RSE measurements will be more sensitive to abundances of H_2SO_4 aerosols and SO_2 due to its inclusion of a Ka band channel. In this presentation, we will discuss the results of retrievals from simulated RSE measurements of Venus' atmosphere.

Several ground-truth atmospheres were assembled using vertical profiles from prior measurements and modelling studies, and absorptivity profiles were generated at 8 and 32 GHz using a microwave propagation model. Radio occultation measurements were then simulated and used to determine the expected measurement uncertainties via linear propagation of errors. Noise was then added to the ground-truth absorptivity profiles using the derived uncertainty statistics. Retrievals were then conducted using the X and Ka band absorptivities from 70 km to the Ka band attenuation limit (45-50 km). The problem of profiling H_2SO_4 vapor, aerosol, and SO_2 from dual band measurements is underdetermined and ill-posed, and we implemented the following procedure to regularize the retrieval. First, an estimate of the H_2SO_4 vapor abundance from the X band measurement is used as the background vapor distribution for a 1-D advection-diffusion model of the Venus cloud system, and several different resulting cloud structures are derived under different assumptions of winds, eddy diffusion coefficents, etc. The cloud model results are then used, along with a parameterized shape model for SO_2, as inputs to an MCMC fitting procedure to determine notional shapes for SO_2 and H_2SO_4 aerosol profiles. The H_2SO_4 and SO_2 profile guesses are then used to seed a non-linear optimization routine with high-pass Tikhonov regularization to estimate the profile abundances at 500m vertical resolution.

In the limiting case of perfect knowledge of all other absorber abundances, the lower limit retrieval uncertainties are determined as 0.2 ppm for H_2SO_4 vapor, 4 mg/m^3 for H_2SO_4 aerosol, and 8 ppm for SO_2 by propagating uncertainty from the measurement covariances. For the conditioned simultaneous retrieval, the uncertainty propagation procedure estimates simultaneous retrieval uncertainties of 0.7 ppm for H_2SO_4 vapor, 18 mg/m^3 for H_2SO_4 aerosol, and 25 ppm for SO_2. From retrieval simulations, we obtain mean errors of 0.4 ppm for H_2SO_4 vapor, 9 mg/m^3 for H_2SO_4 aerosol, and 20 ppm for SO_2. These estimates are valid if the assumptions underpinning our retrieval conditioning are accurate, and achievable uncertainties will be significantly poorer otherwise. While incorporation of the SO_2 transport and chemistry into the transport model may further constrain the retrieval, this is challenging due to limited knowledge of the SO_2 depletion mechanism. As evident from these simulation results, great care will need to be taken in the interpretation of RSE attenuation measurements if reliable estimates of H_2SO_4 aerosol and SO_2 profiles are to be determined. The H_2SO_4 vapor accuracy is excellent, and the results of the joint X/Ka band retrieval can be used to de-bias the X band vapor profile, which reaches lower in the atmosphere (35-40 km).

Potential exploration of the Venus ionosphere with EnVision radio science

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Abstract

Radio science is a useful method for the remote exploration of the ionosphere and neutral atmosphere of other planets. When the spacecraft is moving behind the planet as seen from the Earth, the radio signal is successively sounding the ionosphere and the lower neutral planetary atmosphere, providing information about the ionospheric electron density and the temperature, pressure and density of the lower neutral atmosphere.

The exploration of Venus with Pioneer Venus Orbiter (1978-1992), Venus Express (2006-2014) and Akatsuki (2015-ongoing) provides an unique opportunity for the investigation of the long-term variability of the ionosphere of Venus during changing solar conditions und its unique interaction with the solar wind. With the arrival of the NASA missions VERITAS and DAVINCI and the ESA mission EnVision at Venus, a new decade of Venus exploration will begin. While the primary focus of those missions is Venus' gravity, atmosphere and imaging, none of those future missions currently involves the investigation of the plasma system of Venus, thereby leaving an important part of Venus unexplored for the next decade.

EnVision provides a unique and valuable opportunity for the continued observation of the Venus ionosphere in the next decade. This work will provide a summary of the recent exploration of the Venus ionosphere by radio science, lessons learned and will highlight the opportunities for the Venus ionosphere exploration provided by EnVision.

The evolution of the atmosphere of Venus through volatile exchanges with the interior and escape

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Abstract

As Earth's closest sibling, Venus is key to understanding how a planet becomes or ceases to be habitable. It is also key to understanding the evolution of terrestrial planetary atmospheres, and how present-day atmospheric composition can inform a planet's past, with potential applications to exoplanets. Despite Venus' critical role in comparative planetology, its history and origin remain enigmatic and debated. Available data (atmosphere bulk composition, deuterium to hydrogen ratio, noble gases abundances and fractionation, current escape rate, age of the surface and so on) do not provide straightforward constraints on the evolution of Venus: markers of the evolution depend on the interaction of multiple mechanisms.

We discuss how the atmosphere, surface, crust, and mantle of Venus could have interacted and evolved together through the lens of volatile exchanges. Going from the deep interior to the top of the atmosphere, we describe volcanic outgassing, surface-atmosphere interactions, and atmosphere escape. We include the role of impacts, how magnetic field generation is tied to long-term evolution, and the implications of geochemical and geodynamical feedback cycles for atmospheric evolution. We highlight plausible end-member evolutionary pathways that Venus could have followed, based on modelling and observations. In one scenario, the planet was desiccated by atmospheric escape during the magma ocean phase. In another scenario, Venus could have harboured surface liquid water, until its temperate climate was destabilized, and it entered a runaway greenhouse phase. In a third scenario, Venus's inefficient outgassing could have kept water inside the planet, where hydrogen was trapped in the core and the mantle was oxidized (see Gillmann et al., 2022, Space Science Reviews, The Long-Term Evolution of the Atmosphere of Venus: Processes and Feedback Mechanisms).

Finally, we discuss existing evidence and how future observations by the ENVISION mission will help to refine our understanding of the planet's history. For example, VenSpec-H will measure water, SO_2, CO and HDO. The composition of the present-day volcanic gas will inform models of outgassing and could provide constraints on the interior redox state. The isotopic fractionation of H in the volcanic source could be affect estimations of overall water. VenSpec-M ≈1 micron surface emission data will constrain surface mineralogy (such as tesserae to search for felsic crust and/or sedimentary rocks) and open a window into Venus' past. The Radio Science Experiment will provide invaluable insight into the interior of the planet to refine our knowledge and modelling of its structure and dynamics. Finally, VenSAR and the subsurface sounder will target the surface and shallow layers of the crust and will provide constraints on past lava flows and putative sedimentary rocks, and present crustal properties and structures. Together with the other missions to Venus in the coming decades, ENVISION aims to bridge the gaps in our understanding of Venus' evolution and provide data that will shed light on why it diverged from the Earth.

Synergies Between Venus & Exoplanetary Observations

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Abstract

At the dawn of the space age Venus was one of our primary planetary targets with Mariner, Venera, VEGA, & Magellan missions into the 1980s. These missions revolutionized our understanding of Venus. In the 1990s, as Venus missions were drying up, we started the era of exoplanetary science that has revolutionized our understanding of neighbouring stellar systems and architectures. Now we are entering a new decade of Venus that include new missions like Envision, while exoplanetary science continues to march forward with space missions like TESS, JWST, CHEOPS and PLATO alongside next generation ground based facilities like the ELT. While a great deal of effort in exoplanetary science is focused on finding Earth-like worlds in the habitable zones of neighbouring systems, Venus is often overlooked. Perhaps naively it is often assumed that Venus' surface has been hot, dry and 'dead' for most if not all of its history. Yet a number of recent works have demonstrated that this may [1-4] or may not [5,6] actually be the case. Hence Venus may have once resided in the habitable zone [7].

Envision will afford us the opportunity to better characterize the surface history of Venus. For example, low-resolution Magellan images in the tesserae regions may imply that water once ran on Venus' surface [8]. Envision's high resolution radar imaging will confirm or refute such work. Envision will also provide the high-resolution imaging needed to better ascertain the best and safest places for future landers in the tesserae in order to characterize the surface materials. These may constrain our evolutionary models of Venus. At the same time observational and modelling efforts for Venus and Earth over the past decades have helped us to better understand volatile cycling, weathering, volcanism and outgassing, volatile ingassing, the role of atmospheric composition alongside magnetic fields in atmospheric escape, and thermal history. All of these are discussed as separate sections in our recently published work [10]. At the same time there are mysteries related to the early post-accretion evolutionary history of Venus which may only be examined via exoplanetary studies. We expect to discover and characterize aspects of exoplanets in the Venus Zone [9] of nearby stars via transmission and secondary eclipse methods with JWST, and other future space and ground based instruments, also discussed in our work [10]. In this talk we will discuss how past, present and future discoveries in each community will better constrain our understanding of Venus, and planets in the habitable zone of nearby stellar systems.

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Venus in the Context of Exoplanet Demographics

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Abstract

In our solar system, Venus is the most Earth-like planet, yet at some point in planetary history there was a bifurcation between the two: Earth has been continually habitable since the end-Hadean, whereas Venus became uninhabitable. Indeed, Venus is the type-planet for a world that has transitioned from habitable and Earth-like conditions through the inner edge of the Habitable Zone (HZ); thus it provides a natural laboratory to study the evolution of habitability. In parallel to the progression of Venus science, exoplanet detection methods have become increasingly sensitive to terrestrial planets, resulting in a much needed collaboration between the exoplanetary science and planetary science communities to leverage the terrestrial body data within the solar system. In fact, the dependence of exoplanetary science on solar system studies runs deep, and influences all aspects of exoplanetary data, from orbits and formation, to atmospheres and interiors. Here we describe how the current limitations in our knowledge of Venus are impacting present and future exoplanetary science, including remote sensing techniques that are being or will be employed in the search for and characterization of exoplanets. We discuss Venus in the context of defining the boundaries of habitability, and how exoplanets are enabling tests of potential runaway greenhouse regimes where Venus analogs may reside. These results are forming the basis of an ExoVenus catalog that will be used to prioritize follow-up observations and determine the occurrence rates of potential post-runaway greenhouse terrestrial environments. The development of our exoVenus targets and spectra rely upon the known atmospheric chemistry, temperature-pressure profile, and habitability history of Venus. The planned data acquisition by DAVINCI, EnVision, and VERITAS, are being incorporated into our models to test the expected impact of these missions on the characterization of Venus analogs, and our understanding of how the boundaries of habitability are determined and evolve with time.

Session 3: EnVision observation philosophy and strategy for Venus – posters

Lessons From Mapping Venus at High Resolution: Implications of Small-Scale Resurfacing on Global Heat Flow

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Abstract

Despite their similar size and composition[1], the different geological histories recorded at the surface of Venus and Earth are evidence of their different heat loss regimes. The majority of heat loss on the Earth is due to plate tectonics[2] and gives rise to mantle cooling. The lack of analogous plate tectonics on Venus[3] suggests that more heat is generated in the mantle than can be lost at the surface, resulting in a net warming of the mantle[4]. The apparently reduced surface heat flow on Venus is probably about 8-25 mW m^{-2} [e.g. [5]], and is most likely lost through a variety of methods, such as hotspots, large volcanoes, and rifting. Here we aim to determine new insights in the contribution of smaller-scale resurfacing mechanisms on Venus by analyzing a geological map made at the full resolution of the Magellan SAR data[6]. This study concentrates on the volcanism observed in a single 'F-Map' (12 x 12°) region when mapped at the full resolution (~75 m/px) of Magellan SAR image data. Previous mapping efforts have only been conducted on a regional (1:5,000,000) scale. The region was selected as there are no large topographic rises, rifts, or large volcanoes, nor major tectonic alteration; instead this region appears to be typical of corona and plains materials on Venus.

Mapping at the full resolution of Magellan SAR image data shows some important differences from a regional scale approach. Flow units attributable to coronae increase by 28% compared with a regional scale mapping method. The large range of relative ages of ridge flows suggests that eruptions were initiated and controlled by local stress regimes and melt production rates. In the absence of volcanic centres, these flows are probably fed by a system of dikes, which are common in areas of extension and rifting[7]. Scaling up the 2919 small volcanoes observed in the F-Map to a surface area equivalent to the surface of Venus results in 973,000 small volcanoes or vents over the entire planet, a value similar to the exponential distribution estimate of 931,000[8], but about an order of magnitude greater than the recent, first global catalogue of small volcanoes[9]. Given that this simple analysis is for a 'typical' area of Venus, with no high-density shield fields[10], then we expect that small volcanoes probably make a significant, although by no means solitary, contribution to the resurfacing on Venus[11].

The future use of higher resolution SAR image data (e.g. EnVision[12]) will be able to identify independent sources of resurfacing and heat loss on Venus.

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Microorganisms as potential inhabitants of the lower cloud layer of Venus – lesson from the Earth's observations of extremophiles

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Abstract

In the Solar System Venus is the most similar planet to Earth in terms of size, gravity and mean density [1]. Numerical simulations of 3D climate models support "habitable hypothesis" for the evolution of Venus including the presence of an ocean [2]. Probably due to increasing solar radiation and volcanism about half a billion years ago a catastrophic climatic change occurred making the surface of the planet inhospitable [3]. As a result of convection and other processes potential Venusian life could have migrated from the ocean to the plausibly habitable zone in the lower layer of clouds (approximately 50 km above the planet surface), characterized by low pH values, sulfuric environment and moderate temperature and pressure. Earthly analogues of microorganisms potentially inhabiting Venus clouds could be represented by Acidithiobacillus ferrooxidans bacteria [4]. The results of the spectrophotometric UV-Vis-NIR analysis of Acidithibacillus ferrooxidans bacteria showed significant similarities to the incident radiation wavelength vs. the transmittance correlation obtained for Venus. Further investigations including different strains of extremophiles are currently in progress.

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Viscosity contrasts in the Venus mantle from tidal deformations

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Abstract

The tidal deformations of a planet are often considered as markers of its inner structure. In this work, we use the tide excitations induced by the Sun on Venus for deciphering the nature of its internal layers. In using a Monte Carlo Random Exploration of the space of parameters describing the thickness, density and viscosity of 4 or 5 layer profiles, we were able to select models that can reproduce the observed mass, total moment of inertia, k_2 Love number and expected quality factor Q. Each model is assumed to have homogeneous layers with constant density, viscosity and rigidity. These models show significant contrasts in the viscosity for the upper mantle and the lower mantle. They also favor a S-free core and a lower mantle slightly hotter, but still consistent, than the expected limits. Our conclusions are obtained with no assumption on the chemical composition of the internal layers of Venus nor the thermo-chemical evolution of the planet. We have therefore derived new independent constraints on the internal structure of Venus.

Venus' polar clouds observed by EnVision

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Abstract

Many of the planets in the Solar System have atmospheric polar vortices. Venus seems to have the most variable ones, changing on timescales of less than 24 hours [1]. Venus Express (VEX) confirmed the presence of a giant vortex in the southern pole of Venus, with a morphology much like the one found at the north pole [2]. The South Polar Vortex was observed by VEX for several years at the cloud top and at the lower cloud level (separated by ~20 km). Its inner structure is better seen in thermal infrared images which show warm poles and filaments surrounded by a cold collar (about ~15 K colder) at the upper cloud level [3]. However, the vortex is also observable at near-infrared images sensing the lower atmosphere and in ultraviolet images of the upper clouds.

Due to the characteristics of its orbit, VEX could study neither the morphology nor the dynamics of the north polar vortex. And since VEX, neither Akatsuki nor ground-based observations have been able to resolve the polar clouds, and no numerical model has been able to fully reproduce these vortices and the dynamical processes acting on them.

Fortunately, the quasi-polar orbit of EnVision will allow to get observations of both polar regions repeatedly, so we will be able to study the morphological differences between the two vortices. Moreover, small-scale cloud tracking will luckily be possible near the poles with VenSpec-M on the nightside and VenSpec-U on the dayside. We are also interested in large-scale motions, because studying the dynamical and morphological transition between the polar and subpolar regions at different levels (using near-infrared and ultraviolet wavelengths) would help understanding how the vortex dynamics is coupled to the general circulation of the atmosphere.

Given that the cloud top is about 10 km lower at high latitudes than at the equator [4] and that there are two very different topographies in the north and south polar regions, analysing the influence of topography on atmospheric dynamics is another of our points of interest. Lastly, EnVision could contribute through the study of the cloud top's altitude to the analysis of the formation of the cold collar, as it seems to be formed partly due to the sinking of the clouds poleward [5].

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Vertical Profiles for SO_2, H_2O, and HDO from the Pioneer Venus Large Probe Neutral Mass Spectrometer

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Abstract

We are currently re-analyzing archived mass spectral data acquired during the Pioneer Venus project for the aim of updating the current state of knowledge regarding the vertical profiles for SO_2, H_2O, and HDO. This work is relevant to the EnVision observation strategy, where the major objectives of the VenSpec-H instrument [1] include measurement of SO_2, H_2O, and HDO. We are re-analyzing mass spectra that was acquired *in situ* by the Pioneer Venus Large Probe Neutral Mass Spectrometer (PV LNMS). The PV LNMS was an instrument on board the Pioneer Venus Large Probe (PVLP), which descended through Venus' atmosphere in 1978 [2]. We recently [3] reported on a new analytical model for the LNMS data and extracted the most complete altitude profile for CO_2 (≤60 km) to date.

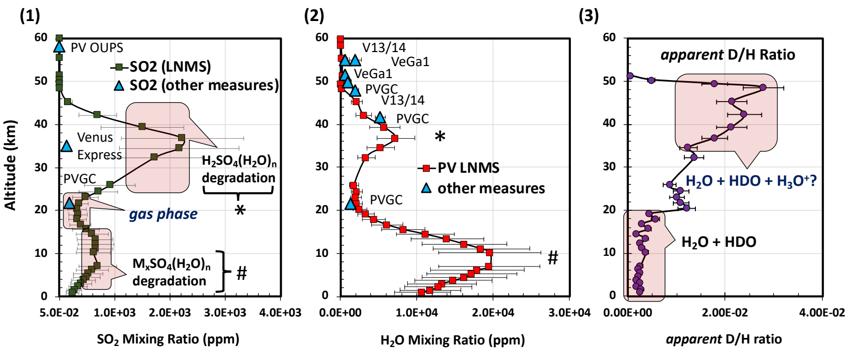

Figure 1. *Vertical profile for SO_2 with delineation of source.* ***Figure 2.*** *Vertical profile for H_2O and comparison to other spacecraft measures.* ***Figure 3.*** *Apparent D/H ratio profile.*

At current, our vertical profiles for SO_2 and H_2O (**Figs. 1-2**) suggest that (1) SO_2 is not well-mixed vertically, (2) total H_2O content in the atmosphere is higher than expected, and (3) both SO_2 and H_2O in the data arise from multiple sources (*e.g.*, gas and aerosol phases, and sulfate degradation). For gas-phase SO_2, we obtain mixing ratios in the clouds at 55.4-51.6 km (3.4 ± 1.9 ppm; 3 σ standard deviation) that are within error to the value at 58 km (4 ppm) obtained from the Pioneer Venus Orbiter UV Spectrometer [4]. Our values in the lower atmosphere at 24.4-16.7 km (340 ± 75 ppm) are also within error to measurements from the PVLP Gas Chromatograph (LGC) at 21.6 km (185 ppm, +350 ppm/-155 ppm; 3 σ), though lower than values from Venus Express at 35 km (130 ± 50 ppmv; 1 σ) [4, 5]. Our trends, therefore, indicate a decrease of ~10-fold in atmospheric SO_2 between clouds and lower atmosphere. Looking ahead, results from the VenSpec-H instrument could confirm these trends.

As shown in **Fig. 2**, we obtain mixing ratios for total H_2O in the clouds (*e.g.*, 297 ± 74 ppm, 51.3 km) that are generally consistent with the LGC (<600 ppm, 51.6 km) and VeNeRa 13/14 gas chromatographs (700 ± 300 ppm, 49-58 km) [5, 6]. However, the range of water abundances (~200-1000 ppm) from these measures greatly exceed water vapor values acquired through telescopic and photometric means (~20-30 ppm) [4]. We suggest that the sampling assemblies of the LNMS and gas chromatographs captured and analyzed water arising from the vapor *and* aerosol phases. We aim to compare those potential *total* water values against measures of cloud water vapor obtained from the VenSpec-H instrument. Moreover, we aim to compare the *apparent* D/H ratio profile (**Fig. 3**) against the VenSpec-H measures to ascertain if the ~10-fold decrease between the clouds and deep lower atmosphere (<20 km) is due to unaccounted isobaric species to HDO, such as aerosol-phase H_3O^+.

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VenCubSAR: a proposal conceptual mission to mapping Venus with a CubeSat SAR

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Abstract

Venus is not only one of the brightest celestial bodies in the sky. Inserted within the limits of the habitable zone of the Solar System, where there are favorable conditions for life, the planet followed a different destiny from its sister Earth. Extreme surface pressures and temperatures; an acidic, dense, and turbulent atmosphere; and a slow and contrary rotation of our orb make up a desolate, and inhospitable scenario. [1,2] Understanding what happened on Venus could be the key to predicting Earth's future. To obtain answers, ESA will send a radar mission about 2030 to map the planet using VenSAR S-Band Synthetic Aperture Radar. Following these governmental initiative, other private ones are already being designed to insert small satellites into the orbit of the brilliant planet, searching for complementary data. So, a new SAR conceptual mission is proposed: Mapping Venus with CubeSat SAR, or VenCubSAR. This mission has been designed by using an X-Band CubeSat SAR capable of mapping spectral responses that potentially could indicate the geological state of the planet. X-Band is expected to provide high-resolution images using the SAR stripmap mode, pointing the Venus surface with side-looking imaging geometry with grazing angles from 20º to 40º [3,4]. The mission overview comprises the use of Model-Based System Engineering (MBSE) to define the phases of the mission following ECSS and NASA standards from the conception to the disposal; the instrumental and spacecraft description (mass less than 300kg), which includes subsystem of the payload and service; the SAR processing algorithm; the orbit insertion, from the expectation of the use of the launch opportunities flying rideshare reaching Venus as a secondary payload; the Concept of Operations; and the estimated cost and risks for a one-year mission. Even the reduced time of the mission, It is expect that the mission be able to collect more information about regions of the planet that has more evidence of volcanism activities, as the area of Maat Mons. [5]

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Session 4: Science complementary with other Venus missions – oral talks

The VERITAS (Venus Emissivity, Radio Science, InSAR, Topography And Spectroscopy) Mission and Synergy with EnVision

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Abstract

VERITAS was selected by NASA as a Discovery class mission on June 2, 2021. Full details on the mission (Smrekar et al. IEEE 2022), the VISAR radar (Hensley et al. SPIE 2020), VEM (Helbert et al., SPIE 2022), and the gravity science experiment (Mazarico et al., LPSC 2023; Cascioli et al., PSJ, 2021) can be found in the referenced articles, as well in accompanying abstracts at this meeting. VERITAS is designed to investigate why Earth and her twin Venus took such different geodynamic and habitability paths. VERITAS' instruments and mission design enable questions that can only be addressed by global high-resolution datasets. The VISAR X-band datasets include: 1) a global digital elevation model (DEM) with 250 m postings and 5 m height accuracy, 2) Synthetic aperture radar (SAR) imaging at 30 m horizontal resolution globally, 3) SAR imaging at 15 m resolution for >25% of the planet, and 4) surface deformation from repeat pass interferometry (RPI) at 2 cm precision for >12 targeted areas. VEM covers >80% of the surface. In combination with the DEM, VEM provides a global rock type map, information of weathering, and a search for recent and active volcanism. VERITAS's low circular orbit (< 250 km, mean 217 km) and Ka-band uplink and downlink to create a global gravity field with 3 mGal accuracy at 155 km resolution – a significantly higher and more uniform resolution than available from Magellan. Knowledge of the moment of inertia factor and love numbers, and thus interior structure, will also be vastly improved over current knowledge.

There are abundant, valuable opportunities for synergy between VERITAS and EnVision. VISAR X-band and VenSAR S-band observations at two different wavelengths allow for enhanced interpretation of surface roughness and thus geologic processes responsible for brightness variations. Interpretation of EnVision's ground-penetrating radar benefits from the VISAR DEM for clutter removal.

Sequential operation of the two missions offers specific enhanced science. Perhaps most important is the ability to search for active geologic processes over as long a timeline as possible (a decade or more). Sequential operation of VERITAS' VEM and EnVision's VenSpec-M (functionally identical instruments) offers the opportunity to search for the thermal signature of active volcanism and the chemical signature of recent volcanism over time. Monitoring of activity, as well as identification of activity, would be impactful. Change detection between radar images over a long duration (Hensley et al. this meeting) would also be extremely valuable, especially when coupled with RPI and VEM observations. VERITAS' global DEM and radar imaging would be could further optimize targeting EnVision's high resolution imaging and play into overall observation planning.

The VERITAS science team is currently conducting two activities with benefit to EnVision. The first is spectral library development for a wide range of igneous rocks and possible weathering products (Helbert et al., Maturilli et al. this meeting). This library of emissivity spectra from the DLR Berlin Planetary Spectroscopy Lab, acquired at Venus temperature, is essential to the interpretation of emissivity from VERITAS, EnVision, and DAVINCI (see also Dyar et al., this meeting). Numerous companion studies demonstrate the issues with reflectance spectra as predictors of emissivity, as well as studies of limitations on weathering products and rates (Helbert et al., Sci. Adv, 2021; Dyar et al. Icarus, 2021; Dyar et al. GRL, 2020). Additionally, VERITAS and DLR Munich/Oberpfafenhofen, our partner for VISAR data processing, will conduct a field campaign in Iceland this summer. DLR's F-SAR plane will acquire x-band and s-band radar data in two areas to address specific science objectives such as change detection between Magellan, VERITAS and EnVision (Nunes et al., LPSC 2023 and this meeting). VEM analogue data (Adeli et al., this meeting) and surface roughness data will also be acquired.

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The DAVINCI Mission to Venus

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Abstract

Introduction: The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission [1] is one of the three missions selected to visit Venus in this decade. The nominal launch date for the DAVINCI mission is June 2029, with probe entry in June 2031 [2,3]. DAVINCI will incorporate two science-driven flybys with a descent sphere atmospheric entry – linking NIR and UV cloud top measurements to *in situ* analytical chemistry measurements from the upper clouds to the near-surface with near-infrared descent images of a tessera surface. DAVINCI's science goals and objectives have been optimized to treat specific questions outlined in the ensemble of recent framework documents including VEXAG goals and the Decadal Survey [2], as well as connecting to other planned Venus missions including the VERITAS and EnVision orbiters.

Flight Instruments and Synergies with EnVision: The DAVINCI Descent Sphere (DS) will carry a suite of five instruments (VASI, VMS, VTLS, VenDI, VfOx). The Carrier-Relay-Imaging Spacecraft (CRIS) carries supporting telecommunications systems and two instruments: VISOR and CUVIS – a near-UV and NIR frame imaging system and a hyperspectral UV imaging spectrometer with internal AI/ML capabilities, respectively.

These instruments are driven by DAVINCI's science goals and objectives to answer key science questions about the Venus atmosphere and surface and yet are synergistic with DAVINCI's sister missions VERITAS and EnVision. The VenDI instrument will image the surface of Venus at Alpha Regio below the clouds, using a band-ratio technique to derive compositional data at scales from ~100 m to ~10 m to compare to EnVision VEM-SPEC instrument data and will derive Digital Elevation Models (DEMs) at 30 m or finer as calibration and validation for EnVision SAR stereo topography and imaging. VASI will measure the dT/dz lapse rate, providing atmospheric context for VEM-SPEC NIR emissivity retrievals. Our two mass spectrometers, VTLS and VMS, will provide isotopic ratios and measurements of chemical species within and below the cloud deck that can be compared with other retrievals, especially by VEM-Spec measurements in the IR. VfOx will provide measurements of the oxygen fugacity at the near-surface providing context for the chemistry of the near-surface environment derived through IR measurements by EnVision. VISOR will acquire night-side NIR frames of multiple tessera regions, including Alpha and Ovda, with retrieved 1 µm emissivity to be compared with VEM-Spec nightside IR. Finally, CUVIS will collect 200-400 nm UV spectra to compare with VEM-SPEC-UV for the upper clouds of Venus. For additional information on these instruments please see Reference [1].

Summary: The DAVINCI mission provides a DS-flyby combination with a chemical laboratory and an environmental package to reveal atmospheric chemistry and environmental context at scales never before attempted at Venus, and with flyby imaging to connect remote sensing to in situ exploration [1]. The resulting data, in conjunction with the data from the EnVision and VERITAS, will place Venus in her context in our solar system and beyond.

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Updates on Japanese Venus Climate Orbiter, Akatsuki

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[2]The same as 1

Abstract

Akatsuki, as known as Japanese Venus Climate Orbiter (VCO) launched in May 2010, is a unique mission to the earth's twin planet, Venus. In contrast to many previous missions, Akatsuki was inserted in a retrograding near-equatorial plane orbit to best characterize the super-rotating atmosphere of Venus and the waves/disturbances of various natures. Akatsuki was best suited to provide the wind field measurements with the largest possible coverage in both temporal and spatial dimensions, especially in the equator to the low latitudes. As of this writing, the temporal coverage has already exceeded 7 earth years since the orbit insertion in December 2015. This almost compares the period of the data acquisition from ESA's Venus Express (2006 – 2014).

By utilizing the data from the near-equatorial orbital pane, Akatsuki has enabled the data assimilation between what are actually measured and what would be predicted from the numerical simulations. This was not possible from previous missions as they were mostly in the polar AND local-time fixed orbital planes. The new world Akatsuki opens is the way to deepen understandings of our Earth while improving the numerical codes to the other planet.

We will present the latest updates of the mission, plus the scientific achievements as well as their implication to wider areas of the science (such as exoplanets) at the conference. Synergy with the upcoming missions are important to thorough understandings of massive atmosphere of Venus.

Revealing the origin and evolution of the Venusian atmosphere with VATMOS-SR (Venus Atmospheric Sample Return mission)

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Abstract

Planetary atmospheres are essential reservoirs controlling a planet's climate and, more broadly, exerting a major control on its habitability through geological time. The composition of the Venus atmosphere is a result of the integration of many physical processes occurring over the geological history of the planet. Determining the elemental abundances and isotopic ratios of noble gases (He, Ne, Ar, Kr, Xe) and stable isotopes (H, C, N, O, S) in the Venus atmosphere is thus a high priority scientific target, as it provides a comprehensive view of the origin and early evolution of the entire planet.

Past space missions provided high value datasets, but the existing measurements are not precise enough to draw firm conclusions and some key measurements (*e.g.* isotopic composition of xenon) are not available. In this work, we will provide an overview of the existing noble gas and stable isotope datasets for the Venus atmosphere. The current state of knowledge on the origin and early and long-term evolution of the Venus atmosphere deduced from this dataset will be summarized. Persistent and new unsolved scientific questions stemming from recent studies of planetary atmospheres (Venus, Earth and Mars) will also be described.

Furthermore, we will provide mission concept details for an atmospheric sample returned by a small skimmer probe that could, within less than two years after launch, provide the data required to bring our understanding of Venus to the same level as Mars in comparative planetology. Such a mission would consist of collecting several atmospheric samples below the homopause during a high velocity entry into the Venus atmosphere. Existing challenges include designing a probe with an advance thermal protection system that is able to tolerate two high-speed atmospheric entries (on Venus and Earth), hypersonic guidance and control technologies required to ensure that the spacecraft is able to stay on course during the atmospheric sampling operation and successfully navigate onto its Earth return trajectory, and developing, with the help of Earth-based verification experiments, sample collection and curation techniques that are able to maximize the scientific output obtained from the analysis of the atmospheric samples.

Observing the effects of present-day volcanism in the Venus atmosphere

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Abstract

We review the signatures and potential detectability of present-day outgassing of volcanic material in the atmosphere of Venus. We first summarize the expected composition of outgassed magmatic volatiles at present time, addressing how changes take place in the lowermost atmosphere. At first, concentrations of these plume gasses are expected to decrease mainly due to dilution through mixing with the air, rather than through chemical interactions. Over longer periods of time, the buffering of atmospheric species with surface reservoirs, aeolian/chemical alteration of surface minerals, and mineral stability at the surface will also affect the concentration of volcanic tracers in the atmosphere. Sulfur dioxide variability at several time scales (from hours to decades) and spatial scales in present day's mesosphere have been monitored since the Pioneer-Venus era, and used as possible evidence of volcanic activity. In addition to sulfur dioxide, water vapor is also particularly useful as a potential tracer for volcanic activity today. Tropospheric water vapor can be measured in-situ but also from orbit at various wavelengths in the infrared range. This review explores expectations of in-situ and remote measurements of volcanic gasses in the atmosphere with particular focus on the upcoming *DAVINCI*, *EnVision* and *VERITAS* missions, as well as possible future mission concepts.

This work is an output of the International Space Science Institute's workshop "Venus: Evolution through Time".

A Multiprong Approach to Identify the Unknown UV Absorber

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Science Goal: *Identify the UV absorption in Venus atmosphere. Characterize the coupling between mesoscale convection, cloud chemistry and the Venus unidentified absorber; estimate their combined impact on the planet's energy budget, and provide data needed to trace feedbacks between the cloud characteristics and the larger-scale circulation. Extend to global maps by data assimilation.*
The unknown UV absorber is integral to understanding the Venus atmosphere. A century-long mystery is the nature of the brightness contrasts observed on Venus's disk. The UV contrasts show the spatial distribution and absorption properties of trace atmospheric species such as SO_2, SO, O_3 and an unidentified absorber whose absorption peaks between 340-390 nm. Multiple candidates have been proposed, including a short-lived sulfur species OSSO, a dimer of SO. The UV absorber may be composed of a mixture of the proposed materials. It may indicate as-yet unknown and/or unconstrained chemical schemes for its production and loss. Thus, identification of this UV absorber is key to the sulfur oxidation cycle, the polysulfur cycle, and the chlorine cycle.

Science Background: The energy balance within a planetary atmosphere is determined by the distribution of temperature as well as opacity sources. As such, Venus' energy budget is directly linked to the variations with altitude, latitude, longitude, and local solar time of SO_2, H_2O, the unidentified absorber, and cloud characteristics, as well as their chemical and dynamic inter-links. Influencing (and possibly influenced by) the equatorial convection are at least two larger-scale phenomena: the planetary-scale, pole-to-equator meridional circulation and planetary-scale gravity waves. These waves alter the brightness temperature at the cloud top, SO_2 mixing ratio, and upper cloud characteristics.
Multiprong Approach for Models, Observation, Assimilation & Interpretation: Correlated observations of trace gases from descent, vertical structure from radio occultation, day side cloud top convection from images, and 3D chemical composition derived from UV and NIR spectroscopy, combined with contemporaneous (within a few days) simultaneous observations of night side convection from NIR imaging and chemistry from NIR spectroscopy will be game changing. These are critical input to identify he absorber and for diagnostic modeling to characterize the couplings between equatorial convection and the larger-scale phenomena. Systematic day side mapping at 0600 to 1800 VLT from 60 S to 60 N at one-hour VLT intervals could match absorbers with cloud features indicative of mesoscale dynamics; and with geographic variations in the unidentified absorbers' opacity at the cloud tops to estimate longer timescale vertical transport… since the lifetime for the unidentified absorber appears to be longer than that of SO_2.

A valuable method for finding realistic global values of a wide range of variables is **data assimilation**, that reconstructs a best estimate of the atmospheric state by combining instrumental observations with an *a priori* simulation provided by a numerical model. Measurement of minor constituents can significantly advance our understanding of the coupled chemistry and dynamics. Measuring trace species can illuminate the complex chemistry, discover heretofore undiscovered species, and determine the spatial distribution and temporal variability of the gases, yielding maps of multiple chemical constituents in Venus' atmosphere at a range of altitudes including cloud altitudes. **These chemical constituents not only serve as valuable tracers, they can facilitate data assimilation techniques to improve the accuracy of the existing Venus GCMs.** For example, the IPSL/LMD GCM incorporates a chemical package that treats and traces 33 constituents, including CO, CO_2, H_2O, SO, SO_2, OCS, and $O_2(^1\Delta)$. Observations of cloud evolution over time will improve the ability to retrieve such species by minimizing uncertainties in the cloud particle characteristics.

A Basal Magma Ocean as a Hidden Reservoir of Noble Gases in Venus

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Noble gases are key to investigating the early and long-term evolution of a planet [1]. Measurements of the abundances and isotopic ratios of noble gases in the atmosphere of Venus are important because they record how the atmosphere formed and has evolved over time [2]. Radiogenic noble gases accumulate in a planet's atmosphere via geologic processes such as volcanic degassing. The NASA DAVINCI Mission [2] aims to use new measurements of radiogenic noble gases to test models of how much volcanic resurfacing has occurred in recent times [3]. Previous efforts to model resurfacing were limited because the atmospheric mixing ratios of many isotopes, especially argon-40 and helium-4, are not well known [1, 2]. However, uncertainties about the interior structure of Venus may also limit interpretations of new atmospheric measurements. In this work, we explore how a hypothetical basal magma ocean (BMO) within Venus may act as a hidden reservoir of noble gases [4], potentially complicating interpretations of DAVINCI's new measurements. Many recent studies have suggested that Earth's mantle crystallized from the middle outwards, rather than from its base upwards. Earth's BMO may have (almost entirely) solidified as late as a billion years ago [5]. If the interior of Venus has cooled slowly relative to that of Earth, then a thick BMO could exist within Venus today. Our geochemical box models (Figure 1), anchored to thermal evolution models [4] and results from mineral physics experiments [6] show that a BMO can sequester up to ~20% of the radiogenic noble gases produced in the mantle of Venus. Thus, studies that assume the mantle has always been fully solidified would tend to underestimate the amount of recent crustal production needed to produce an observed amount of atmospheric argon-40 and helium-4. Fortunately, DAVINCI is not the only mission being sent to Venus. EnVision (and VERITAS) will gather geophysical data (gravity, plus radar imagery and topography) that will provide key constraints on models of the interior structure of Venus [7] and its cooling history [8]. We will discuss how to combine geophysical and geochemical measurements to test models of BMO solidification and crustal production. Ultimately, our work highlights the synergistic potential and critical importance of combining a range of data from the fleet of upcoming missions to Venus.

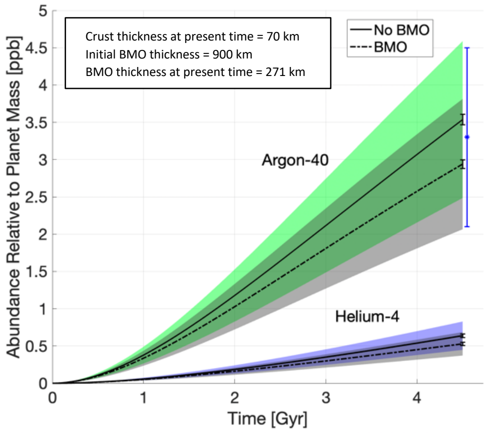

Figure 1. Modelled atmospheric abundances of argon-40 and helium-4 on Venus with and without a BMO. The color bands in the plot represent upper and lower bounds due to uranium abundance uncertainty [4]. Vertical error bars at present time show the projected precision of DAVINCI's Venus Mass Spectrometer [2] (black) and current estimate of argon-40 in the atmosphere (blue) [9].

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Synergy between VERITAS and EnVision for constraints on effusive volcanism

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Abstract

A constraint on current volcanic activity would be of enormous importance for our understanding of the evolution of Venus. Due to the high surface pressure that inhibits exsolution of volatiles, a large fraction of volcanism is expected to be effusive and form lava flows. Incandescent, i.e. actively erupting lava flows can be detected by the NIR imagers VEM on VERITAS and VenSpec-M on EnVision, that have similar performance and coverage. We will discuss the expected number of detections by these two instruments and how this provides a significantly better constraint on the rate of volcanism. The VIRTIS instrument on Venus Express was estimated to be capable of detecting lava flows with an area integrated thermal emission of 1 GW/(µm sr) and thermal modelling relates this to an effusion rate of about 800 m^3/s[1]. The instruments on the new missions will achieve an estimated 60 times better signal-to-noise ratio and thus can distinguish the signal of an effusion rate of 12 m^3/s from atmospheric and instrumental noise. Taking Earth's oceanic hotspot setting as an analogue for eruption duration and effusion rate distributions provides the expected frequency of detectable eruptions for a given global rate of volcanism [1]. Statistics of these eruptions on Earth indicate that the new instruments could detect about 28 % of the eruptions that are active in the field of view. Together with the average eruption volume, the visibility window of eruptions, the coverage of the instrument of the VERITAS mission, this results in an expected number of eruptions of 1.5, corresponding to the probability of detecting at least one eruption of 77 %. Assuming that EnVision with its similar instrument and orbit can expect the same number of detections results in a probability of at least one detection over both mission life times of 95 %. This is already an important synergy between the two missions. Another synergy could be achieved if comparison of radar observations between the two missions could determine the volume of the detected eruptions. The distribution of eruption volumes might follow a power law [3], which means that the problem of determining the global rate of volcanism from a small catalogue of events biased towards larger than average eruptions could be similar to determining the global seismic moment rate from detected seismic events, making applicable the respective analysis approach developed for the InSight mission [4]. While the comparison of radar imagery between the two missions will likely detect more new flows than seen in NIR (provided the missions do not operate at the same time), the direct detection of incandescence is independent of comparison and thus can more easily guide targeted observations to accurately determine the volume of new flows, which is the equivalent of marsquake magnitude and thus might be useful for the estimate of the global rate.

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Back-arc spreading and moving plates on Venus: insights from laboratory experiments

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Abstract

The dynamical regime of Venus today is still unknown, but hopefully this is going to change soon with the next missions to Venus. One major advantage to have missions in succession like VERITAS and ENVISION is that it will be possible to detect deformation « in the making » by comparing high-resolution images taken at different times by the two missions. But this implies to determine in advance the targets for high-resolution imaging. Modelling can help to choose such targets.

This presentation is focused on the possibility of detecting moving plates and plate boundaries on Venus. We investigated in the laboratory convection in a complex rheology mantle using an analog fluid, silica colloidal dispersions. By varying the fluid composition, and the top boundary condition (drying/cooling), we are able to change the depth of the brittle-ductile transition, and therefore the convective regime, as well as its tectonic signatures on the surface. Hence, we showed that plume-induced subduction was likely on Venus, where subduction will proceed through roll-back and accretion could occur in the back-arc basin. Both features are probably occurring in Artemis Coronae today. Another such case could be happening East of Etinoha. On the other hand, subduction could be occurring on the North-West side of Quetzelpetlal coronae. Depending on the nature of Kalaipahoa Linea, the plate between this structure and the subduction trench could be laterally moving toward the trench, and it would be a case where slab roll-back has transformed in slab pull. Scaling laws derived from the experiments suggest that in the three cases, slab roll-back and/or plate velocity could reach 1 to 10 cm/yr, depending on the asthenospheric viscosity. This should be detectable by cross-correlation of VERITAS and ENVISION high-resolution images.

A Laboratory study on end-member mixing for the deconvolution of spectra measured from the Venus Emissivity Mapper

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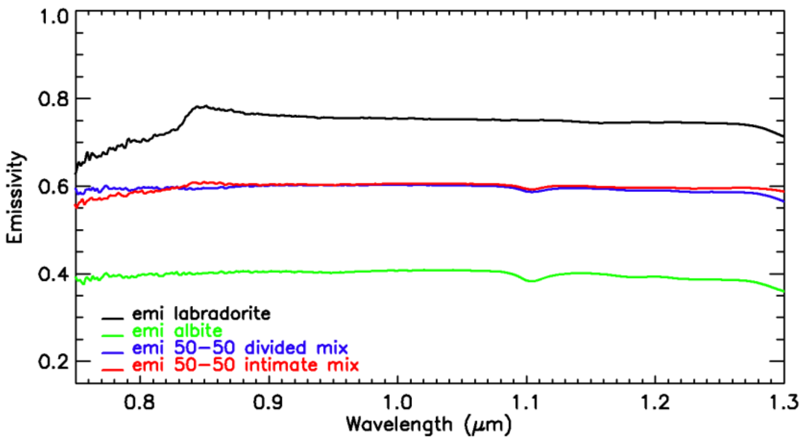
Abstract

In June 2021, ESA selected the mission EnVision (under the Cosmic Vision plan), and NASA selected the VERITAS and DAVINCI missions (under the Discovery program) to study the planet Venus. The Venus Emissivity Mapper (VEM) is part of the NASA VERITAS mission as well as the ESA EnVision mission – here as VenSpec-M channel of the VenSpec suite. VEM will map the Venus surface emissivity using six spectral bands in five atmospheric windows that see through the CO_2-rich atmosphere [1]. VEM also carries eight additional bands for calibration and detection of near-surface water vapor.

The Planetary Spectroscopy Laboratory (PSL) is operated by the VEM PI-team. It is the only facility in the world capable of acquiring emissivity spectra of Venus analogs in vacuum at Venus surface temperatures (routinely 400°, 440°, and 480°C), and hemispherical reflectance (in vacuum at 25°C) in the VEM spectral range [1]. We present here results on spectra of binary mixtures of end-members to improve our understanding of mixing properties at this wavelength and assist with interpretation of VEM data.

For a first study of areal and intimate mixtures of analogues in the VEM spectral range, we chose 4 pairs of end-member samples and relative mixtures. We used three standard sample cups contain the end-members, and an intimate mixture 50%+50% (in volume) of the two end-members, a fourth cup contains surface-separated endmembers. The custom-designed split ceramic sample holder allows to keeping the two end-members spatially separated.



Samples were measured in vacuum at 400°C. The labradorite feature around 0.85 micron is most likely an artifact from the detector. Albite is showing an absorption feature around 1.1 µm, that is characteristic and diagnostic for the material. Spectra of the areal and intimate mixture are almost identical and lie almost exactly between the 2 endmembers and both show the characteristic albite feature. This allows to conclude that at least for this example, the linear mixing of the 2 endmembers can be considered as maintained.

Conclusions: This work is our first step in the process of understanding emissivity spectra of mixtures in the VNIR spectral range: a massive laboratory activity is already planned [2, 3]. Nevertheless, it highlights the difficulties of calibrating emissivity data acquired under Venus conditions, and serves as a reminder of the importance of careful interpretation of individual spectra.

References: [1] Helbert J. et al. *This conference*. [2] Alemanno et al., *this conference*, [3] Dyar et al. *this conference.*

Field campaigns to analyse spectral characterisation of various volcanic material in NIR range; preparation for EnVision and VERITAS

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Abstract

One of the main objectives of the ESA EnVision and NASA VERITAS missions is to understand the evolution of Venus by characterizing the composition and origin of its major geological terrains. The best dataset of surface composition covering the southern hemisphere of Venus comes from the VIRTIS instrument on board the Venus Express mission, which used a near-infrared sensor [1, 2, 3], because the dense CO_2 atmosphere of Venus only allows observations in narrow spectral windows around 1 µm. It mapped the Venusian surface through narrow atmospheric windows at 1.02, 1.10 and 1.18 µm [4, 5]. Despite the fact that VIRITS was not designed for this task, it provided new insights into Venus' evolution and history, such as the discovery that Venus had undergone recent volcanic activity [6]. The VenSpec-M instrument as part of the VenSpec Suite on the ESA-NASA EnVision mission [7] and VEM on board the NASA VERITAS mission [8] will observe the surface of Venus through a broader wavelength range with five atmospheric windows including six bands. These will allow the spectral characteristics of the Venusian surface, as well as the type of lava and likely alteration processes, to be determined in unprecedented detail. To prepare for these missions and deepen our understanding of the emissivity spectral characterisation of various volcanic rocks, we plan several field campaigns using in situ measurements that emulate VenSpec-M and VEM and bring rocks back for emissivity measurements at the Planetary Spectroscopy Laboratory of DLR in Berlin.

Vulcano in southern Italy: Field work in this area was planned as part of the Vulcano summer school [9] in June 2022. Tectonically-controlled magmatic activity is the source of lava for Aeolian Islands and their alignment [10]. Vulcano rocks display diverse compositions from basalt to rhyolite, making this site an attractive analogue to Venus. The island also shows a strong fumarolic activity with very high temperatures. Our main goal was to characterize the spectra from the fresh and old volcanic rocks with different compositions using the spectral range of the VenSpec-M and VEM. See [11] for more information on this campaign.

Iceland: Reykjanes peninsula in Iceland with its very recent eruptions from the Fagradalsfjall volcano, is a prime analogue to Venus. Contacts between the very recent (2022 and 2021), and older altered lava flows, as well as the system of fractures and faults in the area, constitute a prime analogue site. In August 2023, DLR and JPL plan an airborne radar data collection campaign over the Reykjanes peninsula accompanied by field work. Our goal is to collect in situ spectral measurements and relevant samples for characterisation in the Venus Emissivity chamber of the PSL at DLR-Berlin. See [12] for more information and the prepared remote sensing project.

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Seeking Venus on Earth: The VERITAS/DLR Analog Field Campaign of 2023

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Abstract

A keystone to understanding formation and evolution of terrestrial planets in the Solar System and beyond, Venus is covered with familiar features, chiefly volcanic and tectonic in nature. Despite this commonality, the fashion with which such morphological features are arranged has challenged interpretations, and a consensus on the geologic history and geodynamical model for Venus still eludes us. Several factors have complicated the analysis of Venus data. Remote sensing of the surface from orbit has only been achieved for very few wavelengths in the electromagnetic spectrum, and there has been a disparity in spatial resolution among the different data sets. To circumvent these constraints and best prepare for the upcoming Venus missions in the late 2020's and early 2030's, it is paramount to study Venus-analog features found on Earth. In conjunction with colleagues at the German Aerospace Centre (DLR)'s Airborne SAR Missions Group and colleagues in Iceland, the VERITAS Science Team is planning a field-analog campaign to Iceland in the late northern summer of 2023. This campaign will entail both airborne and surface components. DLR's F-SAR airborne radar will image the surface, while a team of U.S. and European VERITAS co-investigators will characterize salient surface properties at different imaged sites. This effort focuses on a variety of targets relevant to volcanic, tectonic, and impact cratering features on Venus while concurrently employing state-of-the art SAR and field techniques. We will use the same techniques as in VERITAS to test our processing of data and their interpretation against the extensive knowledge of these analogs present in the literature and augmented by our field data.

DLR's full-polarimetric, multi-band airborne synthetic aperture radar system is capable of imaging at VERITAS (X-band) as well as Magellan and EnVision (S-band) wavelengths and at incidence angles that subsume those employed by Magellan, VERITAS, and EnVision. Targeting is optimized to maximize cross-track coverage and to carefully overlap successive swaths to sample the same key surface features with both Magellan- and VERITAS-like incidence angles. Resolution of F-SAR data will far exceed the 30 m lateral (global) resolution of VERITAS and will be down-sampled for testing VERITAS analysis tools. Surface measurements will serve not only as calibration and ground truth to the airborne radar data, but it will also serve as a test and guide to our data-processing techniques. At three field regions of interest (ROIs) that bear relevance to Venus, we will measure meter-scale topography, cm-scale roughness and stratigraphy, and surface complex permittivity. These surface properties exert primary control on SAR backscatter. Multiple measurement sites each comparable to the several-meter F-SAR lateral resolution, will be characterized in every ROI. We will also collect VIS/NIR spectra at the same measurement sites to gain insight on the potential relationships between VERITAS' VISAR and VEM datasets.

The VERITAS/DLR field campaign offers a unique opportunity to collect remote sensing and in-situ data that will not only prepare the team for the acquisition and analysis of VERITAS data, but will also potentially enhance the science return from other Venus missions, from Magellan to EnVision.

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The Composition of Venus's Mantle

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Abstract

The composition of Venus' mantle, and its Mg# in particular (MgO/(FeO+MgO)×100, in mol.%), is largely unconstrained. The broad spectrum of possible composition compiled in BVSP [1], named V1 to V5, span widely different Mg# from 76 (V4, Mars-like) to 99.6 (V1, Mercury-like). The analysis by the Venera and Vega landers of basalts resembling terrestrial basalts is often taken as an indicator that the Mg# of Venus's mantle could be more Earth-like. We first critically review the previously proposed mantle compositions. Next, we use thermodynamic and petrologic models described in [2] to calculate the possible mantle sources of the Venera 14 and Vega 2 basalts. We find that mantles of Mg# 83-92 can match simultaneously the concentrations of Al_2O_3, FeO and Mg# of the Venera 14 and Vega 2 basalts, within uncertainty (Fig. 1a-b). Lastly, in Fig. 1c we predict the range of moment of inertia factors (MoIF) consistent with the proposed mantle compositions from Fig. 1a-b. The tighter constraints on the mantle composition set a tighter bound on the MoIF than is currently provided by radar measurements [3]. With future measurements of the tidal deformation and MoIF from VERITAS, and more information on the surface composition from both VERITAS and EnVision, our models will help to place tighter constraints on the bulk composition of Venus.

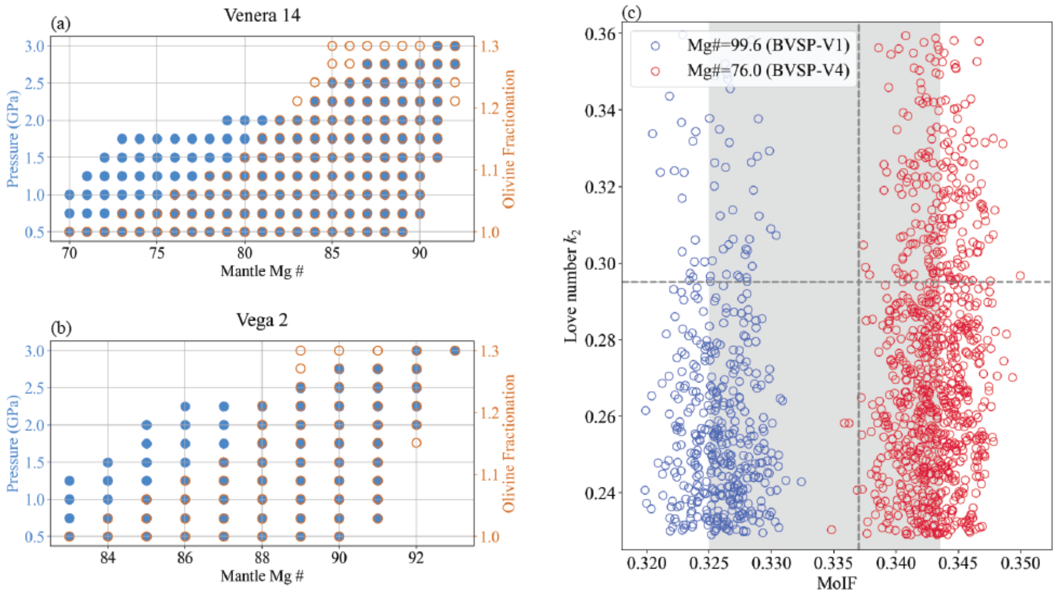

Figure 1: *(a-b) Mg# of the mantle compositions able to produce melts similar to the Venera 14 (a) and Vega 2 (b) basalts, by melting at different pressures (left y axis) with MAGMARS [2]. We allow the Vega and Venera basalts to contain 0 to 30 wt.% additional olivine (1 to 1.3, right y axis) to account for possible olivine fractionation during ascent. (c) The MoIF and the tidal Love number k2 predicted for an ensemble of Venus models with different interior profiles and a fixed mantle mineralogy (V1 or V4, [1]). The empirical mean values of k2 [4] and MoIF [3] are indicated by a dashed line; all samples lie within the 2-sigma interval. The grey field represents the MoIF assuming a Mg# in the range 83-92, the intersection of the ranges displayed in panels (a) and (b).*

References: [1] Basaltic Volcanism Study. Project, 1981. [2] Collinet et al., JGR:P, 2021. [3] Margot et al., Nat. Astron., 2021. [4] Konopliv & Yoder, GRL, 1996.

Thermal Evolution and Interior Dynamics of Venus: Modeling and Observations

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Abstract

Several observations indicate that Venus was volcanically active in the recent past and that magmatic activity may still be ongoing. While the present-day geodynamic regime of Venus's mantle is still debated, models agree that magmatism played a major role in shaping the atmosphere and surface that we observe today [1]. Elastic lithosphere thickness estimates for a variety of geological features on Venus such as coronae [2], volcanic domes [3], and crustal plateaus [4] are directly linked to the thermal state of the lithosphere. These values indicate that at least locally Venus possesses a hot lithosphere and consequently a high heat flux possibly caused by magmatic intrusions.

In this study we present thermo-chemical evolution models of Venus (Fig. 1a) and take into account the effects of extrusive and intrusive magmatism on the interior dynamics. We test thermal histories for purely stagnant lid models and for models in which surface mobilization takes place during the evolution. We estimate the effects of magmatic intrusions on the thermal state of the interior and constrain our models by comparing the obtained thermal gradients to the values estimated from gravity and topography studies [3,4,5,6] (Fig. 1b). Moreover, we investigate the consequences of magmatic intrusions on the thickness of the seismogenic zone on Venus (Fig. 1c), the region where quakes could nucleate, and calculate the tidal deformation at present-day. We discuss how such geodynamical models can use observations from future missions to Venus [7,8] to constrain the planet's present-day interior structure, dynamics, and magmatic activity.

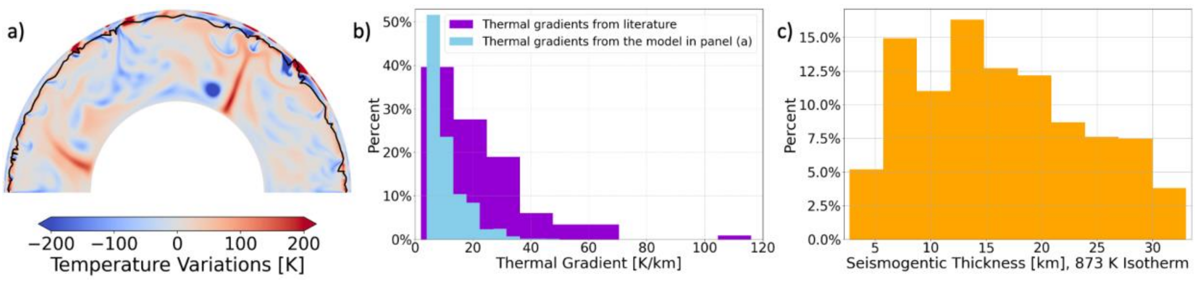

Figure 1: *a) Geodynamical model with 80% intrusive magmatism, assuming an intrusive depth of 23 km, and allowing for surface mobilization. The temperature variations are shown at present day. The black line indicates the stagnant lid thickness; b) Comparison of thermal gradients proposed in the literature and from the geodynamical model in panel a); c) Seismogenic layer thickness calculated at present day from the geodynamical model in panel a). The depth of the seismogenic zone is defined as the depth of the 873 K (600°C) isotherm.*

References: [1] Rolf et al., 2022. [2] O'Rourke & Smrekar, 2018. [3] Borrelli et al., 2021. [4] Maia and Wieczorek, 2022. [5] Smrekar et al., 2022. [6] Phillips et al. 1997. [7] Ghail et al. 2016. [8] Smrekar et al. 2020.

Session 4: Science complementary with other Venus missions – posters

Constraining the Interior Structure and Thermal History of Venus

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Abstract

Often termed the twin sister of the Earth, Venus represents an alternative outcome of the thermal, geochemical, and atmospheric evolution of an Earth-sized world. Yet, despite its proximity to the Earth, it also remains the least explored terrestrial planet in terms of interior structure. The tidal deformation of Venus, indicative of the planet's core size and mantle rheology, has been estimated in 1996 based on the Magellan and PVO data [1], and the moment of inertia factor (MoIF), related to the internal density profile, was recently inferred from radar observations [2]. Other sources of information, such as the absence of a detectable global magnetic field or the elastic properties of the lithosphere, might provide further insight into the thermal state of the Cytherean mantle [3,4]. Still, the uncertainties of the existing measurements preclude the construction of a conclusive interior model.

In this work, we adopt a probabilistic approach and explore the interior structure and thermal state models that match the existing empirical constraints, while also being consistent with 1d thermal evolution models assuming parameterised mantle convection in the stagnant-lid regime. Considering three possible mantle compositions with different iron content and varying a wide range of parameters (e.g., the core size, the initial mantle temperature, and the rheological and thermal parameters), we perform Bayesian (MCMC) inversions and investigate the distributions of the key interior properties (Figure 1). In addition to that, we also discuss the improvements to our understanding of Venus's interior expected from future measurements of the tidal deformation and MoIF from VERITAS as well as information about surface tectonics, volcanism, and composition from both VERITAS and EnVision.

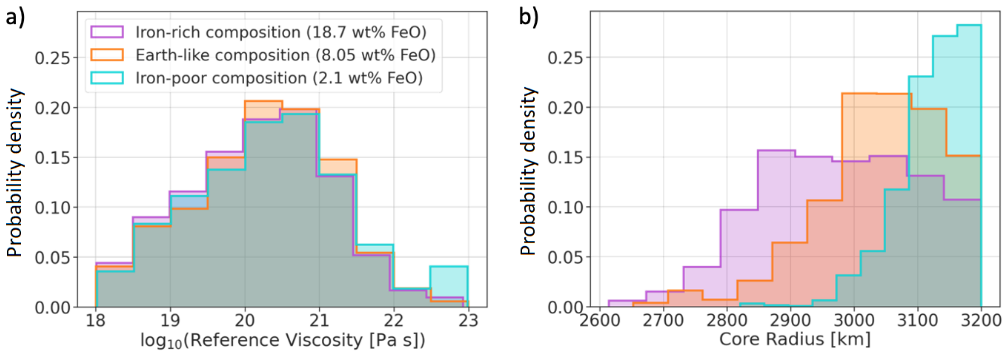

Figure 1: *The marginal posterior distributions of a) reference mantle viscosities and b) core radii corresponding to the three considered mantle mineralogies.*

References: [1] Konopliv & Yoder (1996), *GRL* 23(14):1857-1860. [2] Margot et al. (2021), *Nat. Ast.* 5: 676-683. [3] Nimmo & Stevenson (2000), *JGR* 105(E5):11969-11980. [4] Smrekar et al. (2022), *Nat. Geosci.* 16, 13–18.

VISAR: Bringing Radar Interferometry to Venus

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Abstract

VERITAS is a partnership between scientists and engineers at NASA/JPL and with the German, Italian and French Space Agencies. It is one of four candidate NASA Discovery 2019 missions selected for a Concept Study Phase leading to an eventual NASA selection in the Spring of 2021. VERITAS would carry two instruments, VISAR the X-band interferometric radar provided by NASA/JPL with contributions from ASI and DLR and VEM an infrared spectroscopic mapper provided by DLR. Data from these two instruments would be combined with gravity science data obtained from tracking data of the orbit to investigate tectonic style and ongoing volcanism. After arriving at Venus after a 9-month cruise from Earth VERITAS would begin an 11-month aerobraking phase, which is interrupted after 5 months for 5 months of VEM science observations, before continuing to its final nearly circular polar orbit that varies between 180 and 255 km in altitude where both VISAR and VEM data are collected.

VERITAS mission, was motivated in large part by two mission objectives. The first objective was to obtain global imagery of finer resolution than the Magellan radar and second to obtain global topographic measurements of comparable spatial resolution and accuracy available at other terrestrial bodies in the solar system. VISAR is a vertical polarization single pass radar inter- ferometer with two 3.9×0.6 m antennas separated by an interferometric baseline of 3.1 m. The radar has a look angle of 30◦ which is balance between radar losses and minimizing shadow and layover gaps in the topographic data. Operating with a transmit bandwidth of 20 MHz VISAR has a range resolution of 7.5 m and has an azimuth resolution of 2.1 m. Radar imagery of 30 m spatial resolution with approximately 25 looks is acquired globally and imagery with 15 m resolution and 7 looks is acquired for about 20% of the planet. Topography is generated globally with 250 m spatial resolution and 5 m accuracy using single pass radar interferometric observations. Radar interferograms with a spatial resolution of 250 m (a 125 m options is being studied) and 1800 looks are generated onboard to reduce data volume. Raw data can be downlinked to support checkout and calibration activities as well as for repeat pass radar observations of approximately 12-15 200×200 km sites for surface deformation studies. Thus, the radar operates in essentially one mode with downlink options to support the various resolution data products and repeat pass radar interferometry. This talk will describe the VISAR observations and its contributions to Venus science.

A portion of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The information presented about VERITAS is pre-decisional and is provided for planning and discussion purposes only.

Venus deep interior structure from VERITAS measurements of rotation and tides

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Abstract

The Venus Emissivity, Radio Science, InSAR, Topography And Spectroscopy (VERITAS) mission will orbit Venus over 4 cycles (~3 Earth years) providing low-altitude global mapping of its surface and interior. The radio science experiment will provide high-resolution mapping of the gravity field, allowing to address many open questions pertaining the crust and lithosphere (see companion presentation by Mazarico et al.,), and a precise determination of the time-variable (tidal) gravity field and rotational state of the planet. The gravity experiment exploits state of the art instrumentation, both onboard and on ground. The radio system enables simultaneous, separate, and coherent link in X and Ka band, with expected accuracies of 0.018 mm/s at 10 s integration time for Doppler and 4 cm at 2 s integration time for range. Remarkably, thanks to the multilink configuration these accuracies are expected to be nearly independent of the sun-probe-earth (SPE) angle, for SPE larger than 15 degrees.

Alongside the radio science experiment, VERITAS will fly an X-band interferometric SAR (VISAR) and a near-infrared imaging spectrometer (VEM). VISAR will produce repeated imaging of surface features throughout the 4 mapping cycles, allowing to create radar tie points, thus tying the inertial position of the probe to the planetary body-fixed frame. Leveraging on the combination of tracking data and radar tie points, VERITAS will be able to measure the precession and monitor the variable spin rate of the planet with a much-improved precision.

We will present the predicted VERITAS capability of measuring the moment of inertia, the variable spin rate, and the tidal response of the planet (both to solar and atmospheric tidal action). We will compare the predicted precision with current models of Venus interior and show that VERITAS measurements will deliver tight constraints to models of Venus interior structure.

The Venus Gravity Field from VERITAS

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Abstract

The Venus Emissivity, Radio Science, InSAR, Topography And Spectroscopy (VERITAS) mission will address key science objectives about the geologic and volcanic history of Venus. In particular, the VERITAS gravity science investigation will inform the current Venus structure of the interior, from crust to core. The interior structure will be primarily determined based on the long-wavelength static and time-variable (tidal) gravity field and the planetary orientation; these are addressed by the companion presentation by Iess et al. The high-resolution mapping of the gravity field is important to address geophysical objectives related to crust and lithosphere. By measuring the crustal density and thickness and the lithosphere elastic thickness, constraints on the thermal, tectonic, and volcanic evolution of Venus can be obtained, and complement the datasets collected by the VERITAS InSAR (VISAR) and near-infrared imaging spectrometer (VEM) and by instruments on other missions.

The VERITAS orbital configuration is well-adapted to high-resolution gravity mapping. VERITAS' Science Phase 2 takes place over 4 cycles (~3 Earth years) in a near-polar near-circular low-altitude orbit. The low altitude, between 180 and 220 km, is comparable to Magellan's gravity-mapping cycles 4-6 (periapsis 150-200 km, but with apoapsis 350-600 km) and lower than EnVision's (periapsis 220 km, apoapsis 400-515 km). VERITAS will use the Integrated Deep Space Transponder (IDST) contributed by the Italian Space Agency (ASI), which has heritage from the ESA BepiColombo mission to Mercury. It can simultaneously transmit coherent Ka/Ka and X/X radio signals to Deep Space Network stations. The Doppler noise level requirement is 33 μm/s (integrated over 10 seconds) for a Sun-Probe-Earth angle (SPE) of 15° (where plasma effects are already not negligible), and the anticipated performance is 18 μm/s. For comparison, the Magellan X-band Doppler noise was ~100 μm/s outside of conjunction periods.

We will present results of simulations conducted with the GEODYN II and MONTE orbit determination software. The gravity field is solved as spherical harmonics expansion. The Stokes coefficients up to spherical harmonics degree and order 180 are estimated. A Kaula rule is applied to regularize the high-degree power of the solution, where data coverage and sensitivity are reduced. We will present the expected resolution of the gravity field mapping and describe how physical parameters of interest to address the science objectives will be obtained.

Studies of the Venusian mesosphere based on new mid-IR measurements from MERTIS during the two BepiColombo flybys at Venus

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Abstract

We report on measurements made by MERTIS[1] (MErcury Radiometer and Thermal Infrared Spectrometer) during the BepiColombo mission's close flybys 1 and 2 of Venus in October 2020 (FB1) and August 2021 (FB2). The pushbroom IR grating spectrometer (TIS) of the MERTIS instrument recorded a large number of spectra of planetary radiation from Venus in the 7-14 µm spectral range (715 - 1430 cm^{-1}) for the first time since the Venera-15 Fourier spectrometer experiment FS-1/4 (PMV) in 1983[2]. We show that MERTIS FB data enable reliable retrievals of mesospheric temperature profiles and cloud parameters between 60 and 75 km altitude. They are in good agreement with the results of the Venera-15 mission. This indicates the stability of the Venusian atmosphere on time scales of decades[3,4]. We present preliminary results on the temperature fields of the mesosphere as a function of local time, altitude, and latitude.

These new results are important for extracting current mesospheric parameters and assessing processes in the mesosphere. Thus, they are also of direct interest for the planning and execution of Venus missions such as EnVision or Veritas.

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Investigation of recent volcanic activities using DInSAR and NIR imaging spectroscopy on Reykjanes Peninsula, Iceland, as an analogue for Venus

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Abstract

Introduction: Venus is an analogue in our backyard for both better understanding the exoplanets, and the past and the future of Earth. Revealing the mystery behind the dynamics that shaped the crust of Venus and the evolution of its atmosphere in a way that is currently so different than Earth, requires a thorough understanding of the volcanism on this planet. After nearly 30 years since the disposal of NASA's Magellan spacecraft, we are, once again, counting down for global data of Venus' surface. Both ESA's EnVision and NASA's VERITAS are recently selected orbital missions to Venus, which will be equipped with imaging spectroscopy and radar instruments. The multi-spectral imaging instruments of VenSpec-M on EnVision [1,2] and VEM (Venus Emissivity Mapper) on VERITAS [3, 4] are similar systems designed specifically for mapping the surface of Venus using the near infrared atmospheric windows around 1 µm [5, 6]. In addition to imaging spectrometers, these spacecrafts will be equipped with radar instruments. VenSAR (Venus Synthetic Aperture Radar) on EnVision will be operating at 3.2 GHz (9.4 cm wavelength) in the S-Band, whereas VISAR (Venus Interferometric Synthetic Aperture Radar) on VERITAS will be operating at 7.9 GHz (3.8 cm wavelength) in the X-Band [7] to provide repeat pass SAR images, which will allow interferometry analyses and change detection.

Remote sensing project on Iceland: Iceland's extreme geological activity, including recent volcanic eruptions, makes it a valuable analogue for studying Venus's young surface. Furthermore, it provides an opportunity to deepen our understanding of investigation of volcanic activity through the use of remote sensing data, in preparation for future Venus missions. Here, we present the preliminary results of our remote sensing project to detect volcanic activity and to distinguish between altered and fresh basaltic lava fields on Reykjanes Peninsula, Iceland. In our study, we use combinations of the NIR spectral bands of Sentinel-2 and Landsat 8 missions in addition to Sentinel-1 and TanDEM-X radar images for DInSAR (Differential Interferometry SAR). Our results point to a significant spectral contrast between fresh and older lava flow fields, that formed during the recent eruptions of Fagradalsfjall volcano. Furthermore, we observed inflation and deflation in DInSAR images in the surrounding area before the eruptions. This project also supports the field campaign planned for Iceland by DLR and JPL, in August 2023, to collect airborne radar data and in situ samples for spectral measurements at Planetary Spectroscopy Laboratories of DLR, Berlin [8, 9].

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In-situ Spectral Acquisition in NIR in Vulcano, southern Italy, as Analog to Venus

[1,2]Juniper Gillespie, [2]Solmaz Adeli, [2]S. P. Garland, [2]G. Alemanno, [2]M. D'Amore, [2]A. Maturilli, [2]M. Baqué, [2]E. Bonato, [1]V. Unnithan, [2]J. Helbert

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Abstract

Little is known of Venus. A thick atmosphere obscures the surface, and extreme conditions prevent landers from gathering sufficient data. Although the atmosphere cannot be penetrated within the visible wavelength range, it has long been understood that a window exists in the NIR, at about 1µm, through which the surface can be observed. The VenSpec-M on board ESA EnVision [1] and the (identical) Venus Emissivity Mapper (VEM) on board NASA VERITAS [2], will use these spectral windows around 1 µm to map the surface by observing the surface emission from orbit. These observations are only possible on the night-side because on the dayside the signal is dominated by reflected sunlight from the clouds. In order to better understand the spectral data from these future instruments, a simplified field version of VEM – the VEM emulator or VEMulator - has been set up and was brought to the island of Vulcano in southern Italy to image volcanic materials as an analogue to Venus' surface [3]. Investigation of this area was carried out as part of the Vulcano summer school [4], which took place in June, 2022. Our main goal has been to characterize the spectra from the fresh and old volcanic rocks with different compositions, through four spectral windows around 1µm. The data will be used to understand what calibration and analysis techniques will be useful for the spectral data collected from future higher fidelity VEM emulators as well as the missions themselves. Spectra were extracted from the images and compared to spectra derived from laboratory spectroscopy (at PSL-DLR-Berlin). Flat field corrections were applied for calibration. Results for calibrated spectra of known objects have proven to be comparable, if not immediately recognizable. Further methods of calibration and analysis may need to be consulted before a more concise conclusion can be drawn.

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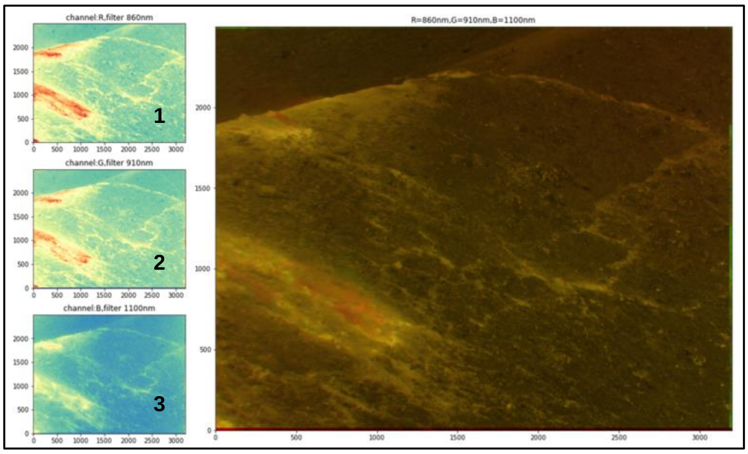

Fig 1: Geometrically registered RGB image, whereas R is 860nm (1), G is 910nm (2), and B is 1100nm (3). The veins where the fumarolic activity takes place are distinguishable as yellow color. The red color shows places with higher fumarolic activity than the yellow veins.

Venus facilities at the DLR Planetary Spectroscopy Laboratory (PSL) in support of the ESA EnVision, NASA VERITAS, and NASA DAVINICI missions

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Abstract

Recently selected Venus missions, including NASA's VERITAS and ESA's EnVision, are equipped with Venus Emissivity Mapper (VEM) instruments [1, 2] focused on the 1 µm region. The VEM is a multi-spectral imaging system designed for global mapping of the surface in all available spectral windows. VenSpec-M it is part of the VenSpec suite on EnVision, along with a high-resolution IR spectrometer and a UV spectrometer. The DAVINCI mission has a descent imager that will also obtain images of the surface around 1 µm.

The Planetary Spectroscopy Laboratory (PSL) at DLR [3] has been operating in support of planetary missions for almost two decades. PSL currently operates three Bruker VERTEX 80V FTIR spectrometers, a Bruker Hyperion 2000 microscope for micro-spectroscopy, and a Terra In-Xitu XRD system for sample characterization. Other sample preparation and analysis tools and experimental sub-systems are also available.

To support orbital surface characterisation of Venus, it is key to obtain emissivity spectra for Venus analog materials in the region from 800nm to at least 1.2 µm at Venus surface temperatures. PSL can measure emissivity spectra of planetary analogues at temperatures up to 1000K in a vacuum environment [4-6]. Hemispherical reflectance measurements at high temperatures have been shown to be convertable to emissivity for most materials. PSL has two hemispherical reflectance units available that can be mounted in the internal chamber of the Bruker VERTEX 80V spectrometer.

The calibration and verification efforts for the VEM and VenSpec-M channel on EnVision include measuring the emissivity of over 100 rock samples at Venus surface temperatures and recording hemispherical reflectance [7,8]. These data will be used for the basic and enhanced calibration datasets for the VERITAS and EnVision missions. However, a good cross-calibration between the missions is essential, and team members from VERITAS, EnVision, and DAVINCI have started discussing cross-calibration efforts.

[1] J. Helbert *et al.*, 2019, doi: 10.1117/12.2529248. [2] J. Helbert *et al.*, 2022, 10.1117/12.2634263. [3] A. Maturilli, J. Helbert, M. D'Amore, I. Varatharajan, and Y. Rosas Ortiz, 2018 10.1117/12.2319940. [4] J. Helbert, et al. , 2021, doi: 10.1126/sciadv.aba9428. [5] M. D. Dyar *et al.*, 2020, 10.1016/j.icarus.2020.114139 [6] M. D. Dyar, et al., 2020, doi: 10.1029/2020gl090497 [7] Alemanno et al., 2023, this meeting [8] Maturilli et al., 2023, this meeting

Local time dependence of Venusian cloud top SO_2 obtained from Akatsuki UV images

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Abstract

The distribution of H_2SO_4 clouds in the Venusian atmosphere is an important factor that influences the solar energy absorbed by Venus. Understanding how SO_2, the precursor of H_2SO_4, is transported from the lower layers to the cloud top where the cloud particles are formed from SO_2 photochemistry is essential for understanding the climate system of Venus.

The UV imager onboard Akatsuki takes images from the orbit around Venus to observe the spatial and temporal distribution of SO_2. Retrieval of SO_2 distribution from these data sets will be important in understanding not only planetary scale but also finer temporal and spatial SO_2 transport. The 283-nm UV images taken by Akatsuki reflect the amount of SO_2 as an absorber at first, but they also include the effects of H_2SO_4 aerosols, unidentified UV absorbers and CO_2 which is the main component of the atmosphere. That makes quantitative discussions difficult.

In this study, we developed a new method to estimate the SO_2 mixing ratio at the cloud top assuming that all UV absorption is due to SO_2 using a newly developed radiative transfer code from UV images taken by UVI under various conditions and estimated the SO_2 mixing ratio during the period from 2016 to 2020. The total number of images analysed in this study is 11243, and we focused only on the results over low latitudes (< 30 degrees) in order to use the same atmospheric model.

From the retrieved SO_2 maps, we derived the local time and latitude mean field of the amount of SO_2. The mean value of the SO_2 volume mixing ratio is from 100 to 200 ppb at the cloud top, which is consistent with the previous study (Belyaev et al., 2012). We found the local time variation of SO_2 has a single peak in the afternoon, which is not consistent with that of Venus Express nadir observation (Marcq et al., 2022), which has two peaks both in the morning and afternoon. We considered that the reason is due to unidentified UV absorbers and recalculated the SO_2 distribution using the mean local time-latitude distribution of the imaginary part of the refractive index of cloud particles obtained by Marcq et al. (2022). However, the major structure remained unchanged and still did not agree with their results. Our results are qualitatively consistent with the vertical SO_2 transport induced by thermal tides, based on the waves' structures reproduced by the GCM (Takagi et al., 2018).

The 365-nm channel of UVI is mostly affected by the absorption by the unidentified absorbers. We are also investigating methods to separately obtain the distributions of SO_2 and unidentified absorbers using both 283-nm and 365-nm images.

Thermal Evolution and Magmatic History of Venus

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Abstract

Venus is referred to as the Earth's twin because of their similar mass and radius, but the present-day surface conditions on Venus are significantly different than on Earth. The hot and dense atmosphere does not allow for liquid water to be stable, however, the situation might have been different in the past. At what point in their thermochemical history Venus and Earth started to diverge is still debated, but it is well accepted that magmatic activity has considerably shaped Venus' surface and interior through time and may be still ongoing today.

Here we present a recently started collaboration between DLR Berlin and the University of Münster. In this project melting experiments will be performed on proposed compositions of Venus to derive melting parametrizations that will be included in geodynamical models (Fig. 1). The latter will be used to model the thermochemical history of Venus and to provide predictions about the present-day level of volcanic and tectonic activity, as well as the degree of chemical heterogeneity in the interior and at the surface of Venus. Our main objectives for this project are to investigate the effects of composition on partial melting in the interior of Venus and to understand what are the consequences of crustal recycling in the presence of volatiles for chemical heterogeneities at the surface of Venus. We will investigate the role of water for the formation of tesserae which are the oldest regions on Venus, whose composition has been suggested to resemble that of the continental crust on Earth.

Our coupled experiments-numerical modeling approach will provide a significant contribution to improve our understanding of the magmatic history of Venus. Furthermore, such an approach can be used to make predictions for upcoming measurements for the recently selected ESA's EnVision and NASA's VERITAS missions.

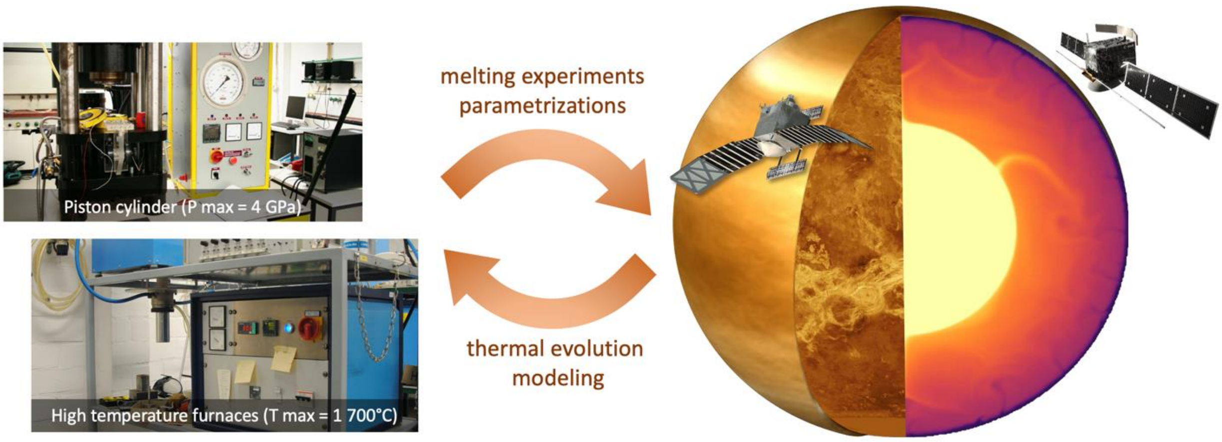

Figure 1: Melting experiments (WWU Münster) will be combined with geodynamical models (DLR) to investigate the thermal evolution and magmatic history of Venus.

Session 5: Activities in support of the EnVision mission exploration – oral talks

Ongoing mantle plume penetration through Venus lithosphere: physical mechanism and implications for EnVision

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Abstract

Mantle plume penetration through lithosphere has been hypothesized for both Earth and Venus with critical consequences for subduction, plate tectonics and global resurfacing initiation (e.g., Gerya et al., 2015; Davaille et al., 2017; Gulcher et al., 2020; Crameri and Tackley, 2017). Physics of this process is incompletely understood but likely includes some rheological weakening mechanisms, such as thermal softening of lithosphere above long-lived plumes (Crameri and Tackley, 2017) and frictional weakening of faults by melts and fluids expelled by the plumes (e.g., Gerya et al., 2015; Gulcher et al., 2020). Whereas on modern Earth this phenomenon is rather limited, Venus surface reveals widespread evidence for many potential cites of ongoing plume penetration into the lithosphere in form of characteristic topography shapes of coronae and novae. The respective corona and nova structures are predominantly located within a large global belt of plume activity (Venus "ring of fire") including the largest Artemis corona (Gulcher et al., 2020). Here, we present recent numerical models based on high-resolution 3D magmatic-(seismo)-thermomechanical experiments, which suggest existence of several potentially detectable features of such active coronae and novae relevant for forthcoming Venus missions. These features include (but not limited to) rapid surface deformation, intense surface and subsurface fracturing, seismic activity of faults, enhanced crustal degassing and elevated heat fluxes. Based on numerical experiments, we propose targeting of specific surface areas by instruments of EnVision mission, which can critically assist understanding and quantification of yet enigmatic mantle plume penetration processes. In particular, radar instruments can sense details of surface and subsurface deformation and fracturing related to rapid corona/nova topography evolution. There should also be potential for detecting melt activities, hot areas (magma outpourings) and outgassing using the VenSpec spectrometers as the numerical models suggest that melt intrusions should come very close to the surface during corona/nova active phase.

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The Viscosity Structure of Venus's Mantle

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Abstract

In the past decade, there has been a growing view that Venus is currently a geologically active planet, presenting signs of recent volcanism and tectonism, as indicated by observations and models [e.g., 1, 2]. Yet, its interior structure and dynamics are still poorly understood. In this study, we investigate geophysical properties of Venus's mantle following the interpretations that Venus's long-wavelength gravity and topography are expressions of mantle convection [e.g., 3]. Making use of the dynamic loading model by [4], we perfom a Bayesian inversion to estimate the mantle density anomaly distribution, assumed to be concentrated in a thin mass-sheet, and the relative radial viscosity profile of Venus. In addition, our analysis adopts the spectral localization technique by [5] to exclude large shallowly compensated highlands, in particular Ishtar Terra, Ovda and Thetis Regios.

Figure 1a shows the distribution of density anomalies predicted by our inversion. Consistent with previous studies [e.g., 6], we found that volcanic rises are correlated with negative density anomalies, whereas the volcanic plains are associated with positive density anomalies. In addition, our predicted viscosity profiles, presented in Figure 1b, indicate the existence of a low viscosity zone in the upper mantle. This zone is characterized by a viscosity reduction of 5-15 times with respect to the underlying mantle. It starts at about 80km depth and has a thickness of 200 km. Drawing a parallel with the Earth, this layer could be a result of partial melting as suggested for the origin of the asthenosphere.

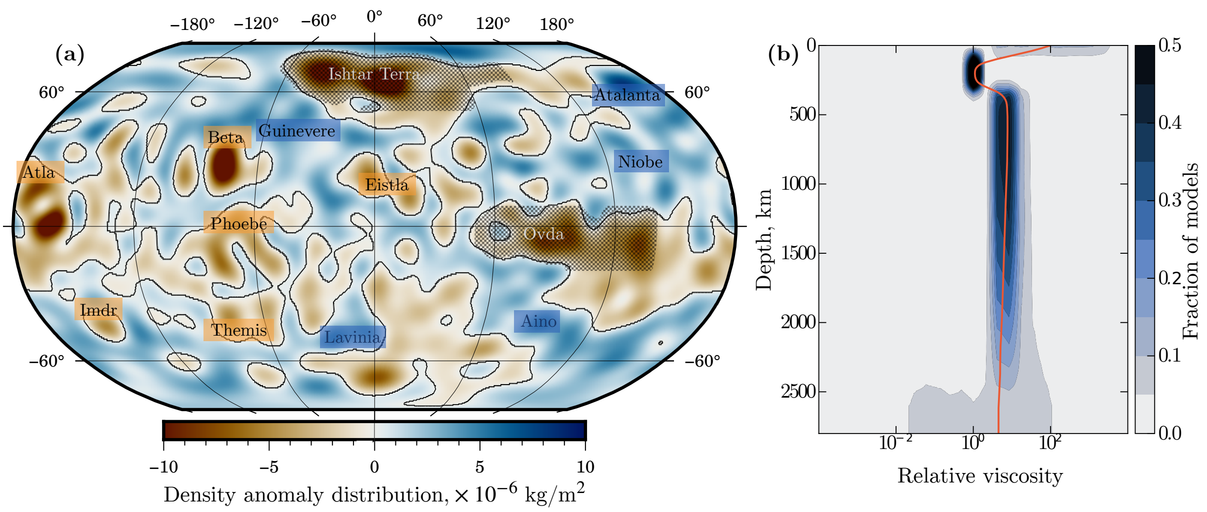

Figure 1: (a) Map in Robinson projection of the density anomaly distribution in the mantle. The shaded areas indicate the regions excluded from our inversions. (b) Posterior distribution of the mantle viscosity structure. The orange curve shows the average viscosity at each depth. All profiles are referenced with respect to the viscosity of the second layer.

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The role of geodynamic modelling of Venus' tectonics and volcanism in paving the way for the 'Decade of Venus'

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Venus and Earth share many similarities, such as size, mass, and chemical makeup. Yet, Earth's environment is habitable, while that of Venus is harsh with a crushingly thick atmosphere over an extremely hot, rocky desert surface. It remains unknown why Earth and Venus have evolved so differently. Upcoming space missions to Venus, such as EnVision and VERITAS, aim to shed light on this mystery. Unlike Earth, Venus lacks a mosaic of mobile tectonic plates. Instead, Venus' global tectonics is putatively driven by mantle upwellings, intrusive magmatism, and lithospheric deformation, resulting in a Venusian surface scarred by many tectonic and volcanic structures. Some of the most intriguing observations are the presence of huge rift structures ("chasmata") and circular volcano-tectonic "corona" structures on the Venusian surface. Unravelling the origin of these features holds clues for the evolution of Venus' interior, volcanism, and even its atmosphere.

Here, we present a geodynamical perspective on the development of Venus' enigmatic corona structures and rift zones. We will focus on recent 3D numerical studies that model the evolution of plume-induced corona formation and rift tectonics on Venus. By comparing the geodynamic model output with planetary mission data, these studies provide key insights into style of mantle dynamics, tectonics, and volcanism on Venus. The morphology of the modelled features seem to directly reveal the activity of tectonic and magmatic processes underneath, and numerous sites of geological activity are proposed on the planet. Thereby, we propose that these coronae and chasmata are key surface targets for instruments of the EnVision mission.

Robust comparisons of available geophysical data of Venus with numerical model results remain difficult. An important goal for the near future is to outline hypotheses on Venus' tectonics and volcanism to be tested with future mission data. For example, volcanic activity (active magma outpouring and outgassing) may be detectable by VenSpec spectrometers and are therefore important to quantify in the numerical models. Moreover, predicting surface fracturing and deformation related to the modelled tectonic processes is relevant since such observables will be sensed by radar instruments aboard EnVision. Finally, computing the gravitational signatures of modelled tectono-magmatic features on Venus (i.e., rifts and coronae is relevant to the future radio science experiments aboard VERITAS and the geological insights made possible by both EnVision and VERITAS. We will present our plan of determining whether we can distinguish between different stages of corona/chasmata evolution in the gravity field and what resolution is needed for such distinctions.

While we mostly formulate above-mentioned key future directions for Venus missions from a geodynamical point of view, we invite all scientists and mission developers to join the discussion on the most effective ways to use numerical modelling tools to pave the way to the 'Decade of Venus'.

Dynamics and Evolution of Venus' Mantle Through Time

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Abstract

The dynamics and evolution of Venus' mantle are of first-order relevance for the origin and modification of the tectonic and volcanic structures we observe on Venus today. Solid-state convection in the mantle induces stresses into the lithosphere and crust that drive deformation leading to tectonic signatures. Thermal coupling of the mantle with the atmosphere and the core leads to a distinct structure with substantial lateral heterogeneity, thermally and compositionally. These processes ultimately shape Venus' tectonic regime and provide the framework to interpret surface observations made on Venus, such as gravity and topography. Tectonic and convective processes are continuously changing through geological time, largely driven by the long-term thermal and compositional evolution of Venus' mantle. To date, no consensus has been reached on the geodynamic regime Venus' mantle is presently in, mostly because observational data remains fragmentary. In contrast to Earth, Venus' mantle does not support the existence of continuous plate tectonics on its surface. However, the planet's surface signature substantially deviates from those of tectonically largely inactive bodies, such as Mars, Mercury, or the Moon. This contribution [1] reviews the current state of knowledge of Venus' mantle dynamics and evolution through time, focussing on a dynamic system perspective. Available observations to constrain the deep interior are evaluated and their insufficiency to pin down Venus' evolutionary path is emphasised. Future missions such as *EnVision*, will revive the discussion of these open issues and boost our current understanding by filling current data gaps; some promising avenues are discussed with this contribution.

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Structural analyses of Latona Corona and Dali Chasma, Aphrodite Terra, Venus

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Abstract

Based on NASA´s Magellan imagery we analyze the structural inventory of Latona Corona and its surrounding chasmata. Coronae are quasi-circular to ovoid volcanotectonic landforms on Venus that are believed to be plume-induced [1]. Latona Chasmata is a circumferential trough that is asymmetric in cross section with steep and wrinkly inner slopes that merge into the corona´s outer annulus and gentle outer slopes that merge into a broad outer rise. The morphologies of the circumferential outer rise and the chasm geometry show similarities to subduction zones on Earth [2], but the elevation differences are less. The outer rise surrounding Latona Chasmata contains a high density of tensile fractures that trend concentrically along its crestline. These fractures can be correlated to the elastic bending of the footwall lithosphere during overthrusting. The steep inner slopes of the chasms indicate convergence and folding and expose faults up of to several hundred kilometers in length, that apparently dip gently towards the corona center. Exposed fault planes appear to have smooth surfaces but the footwalls are associated with megascopic fault breccia damage zones. The scaling relationship of exposed fault length L to the estimated minimum displacement D is similar to that of large faults on Earth and obeys a power law: $D = 0.0456\ L^{0.983}$. We propose that these low-angle faults were initially formed as thrust planes but subsequently became reactivated as low-angle normal faults. Such faults are not restricted to circum-Latona chasmata but are also observed at Dali Chasma northwest of Latona Corona and other chasms. Based on fracture orientation analysis at Dali Chasma oblique overthrusting followed by low-angle normal faulting can be inferred.

The presence of such low-angle faults and their multi-incremental activation are compatible with previous observations [3] and models of corona formation [1, 4]. We propose that a hot asthenospheric mantle plume first led to lithospheric mantle delamination underneath the corona and caused a buoyancy-driven topographic uplift of the corona. This uplift exerted horizontal stresses that led to lateral spreading of the plume. Overthrusting and incipient subduction started in the immediate surrounding of the delaminated lithosphere, where the lithosphere was intact and cooler. The present morphology of the corona indicates subsequent down-sagging and cooling of the corona interior. The high circumferential annulus of the corona is supported by the intact and thickened lithosphere. A reactivation of the thrusts as low-angle normal faults may result from subsidence of the coronas interior, gravitational instability of the elevated corona annulus, and a lack of shortening. We believe that chasmata and associated faults are relevant for understanding the crustal kinematics of Venus and suggest that EnVision and VERITAS missions draw specific attention to these structures.

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Laboratory VNIR emissivity spectra of Venus analogue rocks for EnVision and VERITAS and the VenSpec-M/VEM verification plan

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Abstract

The Venus Emissivity Mapper (VEM) on the VERITAS mission and the VenSpec-M on the ESA EnVision mission are similar multi-spectral imaging systems designed specifically for mapping the surface of Venus using the near infrared atmospheric windows around 1 µm. VEM/VenSpec-M will provide the first global map of rock types on the surface of Venus as well as constant monitoring for volcanic activity at global (VERITAS) and regional/local (EnVision) scales. To correctly interpret VEM/VenSpec-M data and map the Venus surface composition, a proper data verification plan is needed. We outline here a basic plan that not only provides fundamental data needed for VEM and VenSpec-M, but can also be adapted to create data products suitable for calibration of the VenDi (Venus Descent Imager) instrument on the DAVINCI mission. Such use of an integrated calibration plan will benefit all three missions and produce coordinated results that can be directly compared.

The VEM/VenSpec-M verification plan is based on the following steps:

1. Creation of spectral library. To date, at PSL (Planetary Spectroscopy Laboratory at DLR in Berlin [1]) we measured the emissivity of more than 100 rock samples under Venus surface conditions. Based on those measurements, we are confident that the six bands measured by VEM/VenSpec-M will have the capability to distinguish basalt from granite [2] given the predicted performance [3]. It is likely that distinction of intermediate compositions will be possible based on their iron contents. In support of that effort, the spectroscopy verification plan will create several spectral increasingly complex libraries: - The **minimal** database needed to serve the requirement to distinguish basalt vs. granite and to address weathering/coating requires at least 250 samples; - The **basic** database (approx. 500-1000 samples) is needed to span intermediate compositions and characterize mineral phases, mixtures of rock types (quarters), and minerals (particulates); - An **extended** database will contain hypothesis-driven samples (e.g., metallic snow) in keeping with ongoing research questions; - Finally, we expect to add spectra from samples contributed by the Venus **community**. Essential to this endeavour are field campaigns in Venus analogue sites [4] and a variety of close collaboration with research institutes around the world.

2. Calibration using flight models and qualification instrument models. The Venus chamber at PSL is equipped with a NIR transparent window that allows the flight instruments to be mounted for measurements of calibration samples at appropriate surface temperatures.

3. Engineering instrument calibration. On-ground and in-flight calibration are foreseen for the orbital instruments. On-ground instrument calibration will include pre-flight geometric, spectral, and radiometric calibrations based on MERTIS calibration campaign and pipeline.

4. Machine learning models. Igneous rocks are typically classified on the basis of chemical information about Na, K, and Si (e.g., the total alkali vs. silica TAS diagram for volcanic rocks). Because those elements are featureless in the 1 µm region, orbital identifications of Venus rock types instead depend upon transition metals (dominantly Fe) that do have spectral features in that region. Therefore, we will train machine learning models to predict FeO using the growing suites of laboratory calibration data collected with the Venus emissivity setup at PSL [5].

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Strategies for calibration and interpretation of VERITAS and EnVision emissivity spectra

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Abstract

The Venus Emissivity Mapper (VEM) on VERITAS and the VenSpec-M on EnVision will cover >80% and ~25% of the surface (respectively) using six NIR bands located within five atmospheric windows sensitive to iron mineralogy, plus eight atmospheric bands for calibration and water vapor measurements. A comprehensive calibration plan to support both instruments is in progress [1]. Interpretation of the orbital data within the context of the laboratory data requires understanding of contrasting sources of error in both types of measurement.

In the laboratory, Signal-to-Noise S/N on a single measurement for a sample at 400°C is >10. Relative error (two measurements, same sample and temperature, measured independently) is <0.0005%. Sample temperature is monitored by a thermocouple (accuracy < 0.1K) in contact with the emitting surface. The spectrum of a blast furnace slag with the same dimension and geometry as sample slabs is used as a blackbody, measured under exactly the same conditions. Accuracy of emissivity for lab measurements is <0.1%. With absolute emissivity data, it is possible to not only easily distinguish between basaltic and felsic rock types, but also to estimate the FeO of surface materials [2,3]. Total FeO can be used as a proxy for identifying igneous rock types along the fractional crystallization trend.

From orbit, planned emissivity measurements by both orbiters will collect radiance at the top of the atmosphere. Using an atmospheric model, [3] relative emissivity data can be retrieved that are subject to uncertainties due to limited knowledge of atmospheric parameters, including short-term atmospheric variability as well as uncertainty about altimetry [5]. The latter two can be reduced effectively by mission design. Short-term atmospheric variability is reduced by frequent repeated observations. Radar observations using modern radar systems allow to derive altimetry with a much higher accuracy than the currently available data from the NASA Magellan mission. The NASA VERITAS global radar altimetry (DEM with 250 m postings and 6 m height accuracy [4]) will enable VEM (and VenSpec-M) to derive relative emissivity with an accuracy of 1% or better, while EnVision will provide local altimetry at 30m height accuracy. Therefore the highest quality global compositional mapping of VERITAS and Envision rock data must await completion of the VERITAS DEM.

The relative emissivity data provided by both spectrometers will allow mapping the distribution of felsic versus mafic rock types as well as a range of intermediate rock types. Flyovers of Venera and Vega landing sites will further provide the opportunity to derive an absolute calibration. This will enable quantative FeO determination to produce a global map of gradational igneous rock types based on FeO contents.

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Role of the atmosphere-interior coupling on the evolution of Venus' rotation

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Abstract

Venus' rotation is the slowest of all planetary objects in the solar system. It is commonly admitted that it results of the balance between the torques created by the internal gravitational tides and by the atmospheric thermal tides that apply on the planet (Dobrovolskis et Ingersoll, 1980; Leconte et al., 2015; Revol et al., in press). The gravitational tides drive the planet into synchronization (deceleration) while the atmospheric thermal tides tend to accelerate the planet out of this synchronization (Correia et Laskar, 2001). The purpose of this work is to quantify the impact of the internal structure and its past evolution on the gravitational tides and thus on the rotation history of Venus. We determine the tidal gravitational torque from the tidal Love number, k2, and the dissipation function Q, which are computed using a viscoelastic Andrade rheology and interior structure model following the approach of Dumoulin et al. (2017). Using 3D numerical simulations performed as in Gillmann et Tackley (2014) as reference for the past evolution of the thermal profile in Venus' mantle, we compute the gravitational torque since the formation of Venus. Using the present-day atmospheric torque estimated by Leconte et al. (2015) from LMD GCM simulations, we show that the current viscosity structure of Venus must be similar to Earth's, with a viscosity of the lower mantle around 10^{22}-10^{23} Pa.s to maintain the present rotation state at equilibrium. However, this study also highlights the necessity to have a more intense tidal dissipation in the past to initiate the tidal despinning. This would imply a much hotter mantle during early evolution, with a much lower viscosity. Even considering an upper mantle including 20-30% of partial melt (Kervazo et al., 2021) during the first billion years, our calculations show that slowing down Venus' rotation by internal friction alone appears unrealistic from an initial period shorter than 2-3 days. If Venus had an initial rotation comparable to the Earth or Mars, additional processes are required to start the despinning (e.g. oceanic dissipation, giant impacts).

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Investigation of Calcium Minerals and SO2 Gas Interactions under Simulated Venus conditions.

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Introduction: The goal of this project is to expose several Ca minerals from different mineral groups to SO_2 at simulated Venus conditions to assess their reaction rates. Investigations completed by other researchers have shown that SO_2 interacts with elements common in minerals, including Ca [1-3]. By using minerals from different mineral groups, we hope to determine the effect that crystal structure may have on the reaction rates. Thorough understanding of this process may assist in interpreting data collected by EnVision. The Venus Emissivity Mapper (VEM) will be used to identify the presence of transition metals which can inform on the bulk composition of the surface [4-5]. However, the alteration rate of minerals by the SO_2 in Venus' atmosphere has not been constrained, and the thickness of a weathering rind could potentially affect the orbital emissivity signal. Therefore, understanding the weathering rind, its maximum thickness around the parent mineral, and the rate at which it achieves this thickness will be essential for mission data analysis.

Methods: The minerals examined in this work include calcite ($CaCO_3$), wollastonite ($CaSiO_3$), anorthite ($CaAl_2Si_2O_8$), and tremolite ($Ca_2Mg_5Si_8O_{22}(OH)_2$. Each mineral was polished, weighed, wrapped in gold wire and hung in a Thermogravimetric Analyzer (TGA). The TGA was heated to 460°C for 6 to 12 days, and either CO_2/1.5% SO_2 or 99.99% CO_2 is flowed through the TGA at 100 mL/min. Experiments have also been completed at 700°C to decrease the length of the experiment.

The initial samples have all been analysed by X-Ray Diffraction (XRD) to confirm the mineralogy. All samples have been analysed using X-ray Photoelectron Spectroscopy (XPS), Scanning Electron Microscope (SEM), and Energy-Dispersive X-ray Spectroscopy (EDS) to investigate any physical and chemical changes at the surface. The SEM/EDS will also be used to determine the depth of alteration into the sample by observing the cross section which was created using a Focused Ion Beam (FIB).

Results: At the time of this writing, calcite, tremolite, wollastonite, and anorthite have been exposed to 460°C and 700°C in CO_2/SO_2 for 6 days. The samples tested at 700°C are currently undergoing analysis and will not be reported in this abstract. Analysis of calcite completed by XPS detected 15.1 at% of S in the form of sulphate at the surface. Furthermore, the surface did not exhibit a carbonate peak (CO_3^{2-}), implying the conversion to anhydrite ($CaSO_4$). The surface of anorthite only had 5.9 at% of S (sulphate) on the surface, and wollastonite only had 6.1 at % of S (sulphate). Tremolite was found to be impure and contained minor mineral inclusions, which resulted in a mottled colour after the experiment. The dark regions were detected to have a higher abundance of S (4.1 at%) compared to the whiter regions (2.6 at%). Our preliminary results indicate that calcite reacted the most in SO_2, and anorthite the least. These results support other experiments completed with similar minerals at simulated Venus conditions [1-2]. Experiments at longer timescales are planned to calculate the reaction rate.

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Measuring gaseous minor species in the night side troposphere of Venus with VIRTIS-H/Venus Express

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Abstract

From 2006 to 2014, the ESA Venus Express orbiter has provided a wealth of data that has not been fully analyzed yet. Here, using all available and suitable night side thermal spectra provided by the -H channel of the VIRTIS spectral imaging suite near 2.3 µm, we constrained the vertical profiles of various trace gases (CO, OCS, H_2O and/or HDO, SO_2) below the clouds in the 30-40 km altitude range. With the help of an updated version of the radiative transfer model used in our first study [Marcq et al., 2008], our preliminary results confirm previously reported findings [Marcq et al., 2008; Tsang et al., 2009; Arney et al., 2014], especially the increase of CO with increasing latitude as well as the anti-correlation between CO and OCS. New constraints about the global average of SO_2, water vapor and D/H ratio of water vapor are also derived. Finally, correlations with other variables (local solar time, surface elevation) are examined and tentatively interpreted. Such reanalyses of past data sets are relevant more than ever, since they provide background truth for designing future instruments on board recently selected missions towards Venus, such as the high-resolution IR spectrometer VenSpec-H [Robert et al., in prep] onboard ESA's EnVision.

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3D modelling of Venus photochemistry and clouds. Support to VenSpec experiment onboard EnVision.

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Abstract

We present here three-dimensional simulations of the Venus photochemistry and clouds from the ground to the bottom of the thermosphere published in [1]. We will shortly describe the state-of-the-art photochemical and equilibrium cloud model implemented in the Venus Planetary Climate Model (Venus PCM and formerly known as the IPSL Venus Global Climate Model (IPSL VGCM) detailed in [2]). The interactive coupling between dynamics, radiation, chemistry and clouds allows a comprehensive description of the CO_2, CO, sulfur, chlorine, oxygen, and hydrogen species, with tracking of the condensed phase. Regarding the clouds, the Venus PCM calculates the composition, number density, and sedimentation rates of the binary H_2SO_4-H_2O liquid aerosols, based on observed altitude-dependent size distributions. The modelled cloud characteristics and vertical profiles of minor species are found to be in broad agreement with most of the measurements available between 30 and 100 km. In particular, the Venus PCM reproduces the steep decrease of H_2O and SO_2 mixing ratio inside the cloud layer, as well as the observed vertical distribution of species well identified above the clouds, such as CO and O_3. The model also agrees with the ground-based measurements of HCl, but not with the conflicting HCl vertical profiles derived from Venus Express. On the quasi-horizontal plane, latitudinal contrasts in the modelled trace species mostly result from the Hadley-type mean meridional circulation. Large-scale longitudinal variations are essentially created by the diurnal thermal tide above the clouds, and by photolysis above 80 km. Owing to its fascinating richness and complexity, modelling the photochemistry of Venus is a difficult task. Some of the challenges still facing current models include the diversity of the chemical families involved, the key role attributed to species not yet measured in the atmosphere, or the incomplete knowledge of the kinetics. Added to this is the thick global cloud cover of Venus, at the origin of strong variations in the chemical composition between the lower and upper atmosphere, which remain poorly understood. The VenSpec spectrometer suite onboard EnVision mission is set to map trace gases above and below the cloud layers with an unprecedented large spectral range due to the three dedicated spectrometers operating in cooperation with each other. We will also discuss the future work that will be done at the IAA to improve the Venus PCM in regards to the scientific support to VenSpec.

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Impact of the turbulent vertical mixing on the Venus cloud chemistry

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Abstract

Venus is hosting a global sulfuric acid cloud layer between 45 and 70 km which has been investigated by the Venus Express and Akatsuki mission. The variability of the cloud convective layer with latitude and local time was assessed [1,2]. At cloud-top altitudes, large bow-shape waves stationary above the main equatorial mountain were observed with Akatsuki [3,4]. One of the main questions that remains unclear about the dynamics of the Venusian atmosphere is how this convective cloud layer and mountain waves mix momentum, heat, and chemical species.

The dynamics of the small-scale turbulence was studied with innovative models [5,6]. The three-dimensional structure of the convective layer was determined, and the mixing with idealized chemistry were quantified. The large bow-shape waves were model, and are mountain waves with a complex vertical propagation. We proposed to use these models with a full chemistry network to study the impact of this turbulence on the chemical species in the cloud.

To study the convective layer and the bow-shape waves, a Large Eddy Simulations (LES) model [5] and a mesoscale model [6] have been developed using the Weather-Research Forecast (WRF) non-hydrostatic dynamical core [7] coupled with the IPSL Venus GCM physics package [8] and the photochemistry model [9]. The chemical network has 38 spices as well as a simplified microphysics scheme. The LES model has a resolution of 400 m with double periodic horizontal condition over 60 km, whereas the mesoscale model has a resolution of 40 km with IPSL Planetary Climate Model [8] forcing the domain horizontal boundary, both from the ground to 90 km.

It is the first time that the interaction between the dynamics and chemistry of the atmosphere is studied in this spatio-temporal scale, and will help quantify the observabilty of small-sclae features by the VenSpec-U instruments

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The Venus Climate Database

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Abstract

The Venus Climate Database (VCD) is a tool designed to be useful for engineers and scientists in need of a reference atmosphere of Venus for mission planning, observations preparation, analysis and interpretation. This project is funded by the European Space Agency, in the frame of the EnVision mission to Venus.

VCD atmospheric fields are based on simulations of the Venusian atmospheric climate by the Venus PCM[1]. It provides mean values and statistics of the main meteorological variables (atmospheric temperature, density, pressure and winds) as well as atmospheric composition and related physical fields for any given point in space and time. It extends from the surface up to and including the thermosphere (~250km), with extrapolation for higher altitudes. The database contains high resolution temporal outputs (using 24 hourly bins) enabling a good representation of the diurnal evolution of quantities over a climatological Venusian day. Several conditions (scenarios) can be chosen from : various Extreme UltraViolet (EUV) input from the Sun (solar minimum, average and maximum, given Earth date, or chosen E10.7 index), combined with different values (minimum, standard or maximum) of the cloud UV albedo to bracket observed variations.

In addition to the climatological values, the VCD provides the Venusian intra-hour variability (RMS) of main meteorological variables, as well as the Venusian day-to-day variability thereof, as estimated from the multiple Venus days of V-PCM simulations. Perturbations can also be introduced in the provided values : (i) large-scale perturbations representative of the large-scale waves present in the V-PCM simulations, through use of EOF decomposition; (ii) small-scale perturbations representative of gravity waves, tuned to reproduce available observations (e.g. VeXADE torque measurements). For deep atmosphere applications, a “high resolution mode” is also available: although the Venus PCM simulations have been run at the resolution of a few degrees in longitude and latitude (3.75° x 1.875°), the VCD uses some post-processing and a high resolution topography map (at 23 pixels/degree) to adjust the local pressure (and density).

These features will be illustrated through applications to EnVision and other future missions to Venus. These applications demonstrate how to interface the VCD with different scripts and codes that need to access realistic atmospheric conditions in any point (space / time) of the Venusian atmosphere.

The VCD (v2.2) is available here : http://www-venus.lmd.jussieu.fr/, providing a simple web interface and the request form to get the full VCD suite.

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Mesoscale meteorology of Venus revealed by Akatsuki and expectations for EnVision

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Abstract

Mesoscale processes, which are much smaller than the planet, are thought to play crucial roles in the climate system of Venus. The complex cloud morphology observed in the ultraviolet wavelength region suggests that the Venusian atmosphere harbors a variety of mesoscale dynamics and associated cloud processes that are yet to be elucidated. JAXA's Venus orbiter Akatsuki has been conducting continuous observations of the atmosphere using infrared and ultraviolet imaging and radio occultation, allowing investigation of mesoscale processes with various methods.

High-resolution, continuous imaging observations of the cloud top conducted by the cameras onboard Akatsuki has identified ubiquitous presence of topographically-generated (mountain) gravity waves and revealed their geographical/local time distributions [Fukuhara et al. 2017; Kouyama et al. 2017]. They were found to appear mostly above highlands and in the afternoon. The extension of wave trains both upstream and downstream directions was observed [Fukuya et al. 2022]. The vertical propagation of gravity waves through the near-neutral layer inside the cloud was modeled to interpret the observed wave characteristics [Yamada et al. 2019].

Gravity waves have been observed also in radio occultation temperature profiles. Applying a radio holographic analysis to the recorded phase time series, high vertical resolution profiles were obtained [Imamura et al. 2018]. The statistical properties of wave packets were studied to show the occurrence of saturation [Mori et al. 2021]. The meridional distributions of the wave amplitude for different vertical wavelength ranges were revealed.

To constrain the origin of small-scale UV contrasts at the cloud top, utilizing the multi-wavelength imaging capabilities of the onboard cameras, the correlation of the cloud morphology between wavelengths was studied [Narita M. et al. 2022]. The results indicate, for example, that elevated clouds are cooled by adiabatic expansion or the ambient air, and that SO_2 is transported to the cloud top region during cloud ascent. The temporal variation of the magnitude of the small-scale UV contrast was studied and shown to have periodicities of 4–5 days synchronized with planetary-scale oscillations.

EnVision, having a capability of high spectral resolution imaging of the atmosphere and the radio occultation measurement, provides a unique opportunity to study the relationship among the spatial/temporal variations of various physical quantities associated with mesoscale processes. The lessons from Akatsuki and expectations for EnVision will be discussed in the presentation.

Long-term Studies of the Venusian atmosphere with the Radio Science Experiment VeRa on Venus Express

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Abstract

The Venus Express Radio Science Experiment VeRa performed regular radio-sounding experiments of the Venus neutral atmosphere using the spacecraft radio subsystem in the one-way radio mode at X-band (8.4 GHz) and S-band (2.3 GHz). The radio link was stabilized by a dedicated onboard ultrastable oscillator. More than 1000 atmospheric profiles could be retrieved between July 2006 and January 2014. Radial profiles of neutral number density from the atmospheric-induced Doppler shift during the occultations cover the altitude range from the upper troposphere (~40 km) to the upper mesosphere (~90 km). These are then used to derive vertical profiles of temperature and pressure.

The spatial coverage of radio occultation measurements is generally quite limited, but the extensive VeRa data set covers almost all latitudes, longitudes and local times. This provides the unique opportunity to study the global atmospheric structure and dynamics at a high vertical resolution.

Static stability profiles retrieved from the data provide valuable information about atmospheric instabilities in the region of the middle cloud layer. Small-scale fluctuations in the thermal profiles reveal a significantly enhanced gravity wave activity in the adjacent lower mesosphere with a strong latitudinal gradient.

Global scale wave phenomena can also be retrieved from the data set. Thermal tides are especially pronounced in the low latitudes with a dominating semidiurnal wave structure in the upper mesosphere. The tides are generated in the cloud layer and propagate upwards and downwards from this region leading to a redistribution of momentum and energy in the Venus atmosphere.

The thermal profiles can also be used to retrieve zonal winds if the assumption of cyclostrophic balance is applied.

The presentation will give a comprehensive overview of the atmospheric scientific results that could be achieved with VeRa in view of the radio occultation studies planned with EnVision.

The EnVision radio occultation experiment is part of the Radio Science Experiment (RSE) on EnVision. Compared to Venus Express, its much shorter orbit provides the opportunity to study the Venusian atmosphere with an exceptionally good spatial and local time coverage to reveal short-term local atmospheric changes. The use of Ka-band, which has never been used to sense the Venus atmosphere so far, allows (in combination with X-band) to study the H_2SO_4 absorption in the Venus cloud layer due to its high sensitivity to sulfuric acid absorption in the liquid and gaseous phase.

Previous and future radio occultation observations of sulfuric acid and sulfur dioxide in the atmosphere of Venus

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Abstract

The main cloud deck within Venus' atmosphere, which covers the entire planet between approx. 50 and 70 km altitude, is believed to consist mostly of liquid sulfuric acid. The temperature below the main clouds is high enough to evaporate the H2SO4 droplets into gaseous sulfuric acid forming a haze layer which extends to altitudes as deep as 35 km. Previous radio occultation measurements at Venus were performed at frequencies lower than 8.4 GHz (X-Band). While liquid sulfuric acid cannot be detected at these frequencies, gaseous H2SO4 is responsible for a strong absorption of the radio signals. The latter was observed in Mariner, Pioneer Venus, Magellan, Venera, Venus Express and the ongoing Akatsuki missions. The radio wave absorption measurements can be used to derive the amount of H2SO4 in Venus' atmosphere. We present H2SO4(g) results derived from these missions at different latitudes and compare them with model results.

The dual-frequency radio occultation measurements at frequencies of 8.4 GHz (X-Band) and 32 GHz (Ka-Band) which will be performed with the EnVision spacecraft provide for the first time the possibility to detect simultaneously the amount of gaseous and liquid contents in the Venus atmosphere. Expected H2SO4 profiles are modelled for different EnVision orbit scenarios. We present the comparison of the previous observations with the expected EnVision H2SO4 profiles which emphasize the improvement of the former results.

In addition to H2SO4 profiles, radio occultation measurements allow to derive the amount of sulfur dioxide in the vicinity of the cloud base. Previous SO2 results obtained by VeRa and those expected from the EnVision radio occultation measurements will be presented.

Venusian atmospheric structure revealed by Venus Express and Akatsuki radio occultation measurements

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Abstract

Radio occultation technique is one of the most useful methods to investigate a vertical structure of a planetary atmosphere because it enables us to retrieve a vertical temperature profile precisely. In the case of Venus, we can retrieve the vertical temperature distribution from the sub-cloud region to the mesosphere (40–90 km).

We analysed Venus Express and Akatsuki radio occultation data to investigate the mean thermal structure (zonally and temporally averaged temperature and static stability distributions) in the Venus atmosphere. At latitudes equatorward of 75˚, static stability is consistent with previous in-situ measurements: a low-stability layer exists at 50–58 km altitudes and highly and moderately stratified layers above 58 km and below 50 km, respectively. On the other hand, at latitudes poleward of 75˚, a deep low-stability layer extends down to 42 km, which has been unreported by previous measurements. We compared the radio occultation measurements with the GCM named AFES-Venus to find that the observed thermal structures are attributed to not only radiative processes but also dynamics such as mean meridional circulation and waves.

Vertical structure of the thermal tides, which is one of the most components to understand the mechanism how the Venusian atmospheric super-rotation is generated and maintained, was also investigated in the equatorial region by the Akatsuki radio occultation measurements. The phase of the diurnal tide little varies in the vertical direction, but that of the semi-diurnal tide tilts toward earlier local times with increasing (decreasing) altitude above (below) 60 km and 50–55 km altitudes, respectively. This suggests that the thermal tides propagate upward (downward) above (below) these altitudes; it is the first discovery to detect the downward propagating component of thermal tides, which is thought to play a crucial role of generating and maintaining the Venusian atmospheric super-rotation.

Vertical profiles of sulfuric acid vapor (H_2SO_4) and sulfur dioxide (SO_2) in the Venus atmosphere obtained by the Akatsuki radio occultation measurements

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Abstract

On Venus, clouds exist at the altitudes from 45 to 70 km, covering the entire planet. This thick cloud layer plays a key role in controlling the heat budget in Venus atmosphere. The major component of the cloud particles is sulfuric acid (H_2SO_4), which also exists as H_2SO_4 vapor in and under the cloud layer. Sulfur dioxide (SO_2) is one of the important chemical compounds in forming the H_2SO_4 clouds. We have derived the vertical profiles of H_2SO_4 and SO_2 mixing ratio using the radio waves' intensity data obtained in the Akatsuki radio occultation (RO) measurements. We newly proposed the method to derive the SO_2 vertical profiles in the cloud layer (50-55 km) by RO, provided that H_2SO_4 vapor cannot be supersaturated in the cloud layer. We attributed any attenuation of the radio waves that exceed the saturation curve of H_2SO_4 vapor to the attenuations by SO_2. In the presentation, we will show the spatiotemporal distributions of H_2SO_4 and SO_2, especially focusing on the local time dependence and the long-term change.

Spatial and temporal variabilities of clouds and chemistry on Venus and their implications for atmospheric processes

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Abstract

Venus, the Earth's evil twin sister, has regained great attention from planetary scientists in the recent years because of the multiple (at least 3) upcoming Venus missions. Understanding Venus is crucial for understanding the evolution of terrestrial planets and predicting the future of Earth. Thanks to the ground- and space-based observations in the last few decades, we have learned that the Venus atmosphere has significant variabilities in chemistry and cloud properties. However, the atmospheric processes responsible for these variabilities remain unclear. Here, we use the state-of-the-art Venus models to understand these variabilities. First, we studied the temporal variabilities of SO2 and H2O at the cloud top (Shao et al. 2020). The two species are temporally anti-correlated. Through a 1D chemical kinetics model, we found that the anti-correlation can be explained by the sulfur chemistry, while the temporal variations may be caused by the lower-atmosphere perturbations. Second, we investigated the local-time variability of chemistry in the mesosphere of Venus, through the combination of a 3D general circulation model and a 2D chemical-transport model (Shao et al. 2022). We found that the local-time distribution of SO2 in the upper cloud can be explained by the thermal tides and the zonal winds, while in the upper mesosphere, it can be caused by photochemistry and the day-night circulation. Other species, including H2O and CO, possess different local-time patterns, resulting from the competition between dynamics and chemistry. Nevertheless, some species, like OCS, still require more observations to confirm their local-time patterns.

Finally, we are studying the spatial and temporal variabilities of the Venus clouds. We are developing a 3D Venus climate model that includes the sulfuric acid cloud physics (Dai et al. 2022), based on the flexible atmospheric model OASIS (Mendonca & Buchhave 2020). We will use our GPU-enabled model to simulate the 3D cloud structure on Venus in high horizontal resolution. We will uncover the atmospheric processes underlying the observed cloud characteristics. Further in the future, our model will resolve atmospheric chemistry on Venus. This would greatly help the science preparation for the Envision mission. This model will also be applied to Venus-like exoplanets to understand the planetary habitability and diversity. Our works highlight the complexity of the Venus climate system and the great need for more observations to better understand this system.

A new constraint on HCl abundance at the cloud top of Venus

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Abstract

We provided a new constraint on HCl abundance at the cloud top of Venus by infrared spectroscopy using a cross-dispersed high-resolution echelle spectrograph, iSHELL, mounted on the NASA Infrared Telescope Facility (IRTF). This study investigated the inconsistency in HCl abundance between previous ground-based observations and Venus Express solar occultation measurements. Venusian dayside observations at a solar phase angle of ~90° were conducted during August 6–7, 2018, and August 18–20, 2020 (UT), when the Venusian afternoon and morning sides were visible, respectively. The high spectral resolving power of ~80,000 and large Doppler shift (~13 km/s) enabled the measurement of Venusian lines with less contamination by terrestrial lines. We analyzed the $H^{35}Cl$ P(5) and $H^{37}Cl$ P(6) lines at 2775.8 and 2750.1 cm^{-1}, respectively, in the 1–0 band, together with $^{16}O^{12}C^{18}O$ P- and R-branch lines of the 20001–00001 band, which fell in the same spectral orders as the HCl lines. The $^{16}O^{12}C^{18}O$ lines were used to derive the cloud top altitude because the upper clouds significantly impacted the retrieval of HCl abundance. The cloud tops had an equatorially symmetric structure. The average altitude was 70.8 ± 0.6 km in the region equatorward of ±30° and decreased toward higher latitudes. The HCl volume mixing ratio was derived as 0.379 ± 0.013 ppm at a probing altitude of 70.6 ± 1.1 km and showed no significant latitudinal dependence within the range of ±70°. A difference of ~0.02 ppm between 2018 and 2020 would result mainly from temporal variation. The $H^{35}Cl/H^{37}Cl$ abundance ratio was 3.01 ± 0.16, with no prominent latitudinal dependence. The obtained HCl volume mixing ratio agreed with the results of previous ground-based measurements, which were approximately one order of magnitude larger than those derived from Venus Express solar occultation measurements. The systematic uncertainties in our retrieval analysis cannot explain this significant inconsistency. The impact of diffuse light produced from aerosol scattering on the retrieval method for solar occultation measurements should be investigated further to solve this issue.

Hunting for meteors on Venus

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Abstract

Meteors and bolide phenomena caused by the atmospheric ablation of incoming meteoroids have so far been detected in the atmospheres of the Earth and of Jupiter [1]. Meteors are also predicted to occur at Venus [2] and have recently become relevant to the search for optical counterparts of radio emissions believed to originate from lightning [3,4]. If carried out systematically, Venus meteor searches would characterise, for the first time, the millimetre to metre meteoroid environment of a terrestrial planet other than the Earth and one that also happens to be our nearest planetary neighbour.

By adjusting existing techniques to simulate meteoroid ablation in a Venus-like atmosphere [5-8], we show that Venusian meteors are generally brighter but shorter-lived than terrestrial meteors and ablate at a higher altitude, in a predominantly clear region of the atmosphere. We further quantify the detection efficiency for optical monitoring of the atmosphere from orbit and determine the suitability of imagers expected to operate in the vicinity of Venus for meteor surveying.

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Session 5: Activities in support of the EnVision mission exploration – posters

Revisiting Venus’ Microwave Emission Spectrum: Implications for VenSAR

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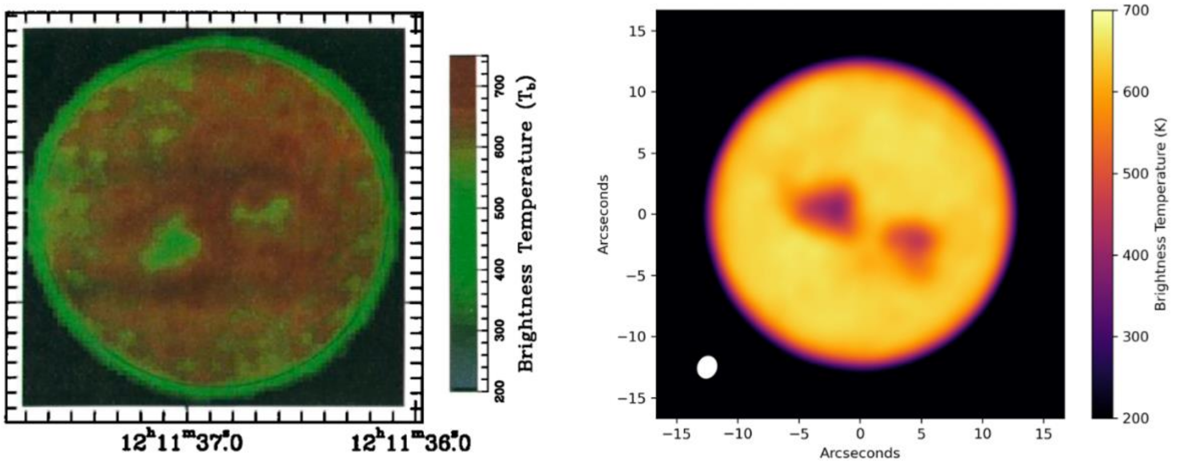
Abstract

Measurements of Venus’ microwave emission (defined here as ranging between 1 millimeter – 1 meter wavelength) from ground-based radio telescopes and spaceborne microwave radiometers have been undertaken for close to 70 years, and as a result, we now have a reasonably accurate estimate of the planet’s disk-integrated spectrum. We still have much to learn, however, about how Venus’ polarimetric brightness temperature spectrum changes over a range of spatial and temporal scales. VenSAR passive radiometer mode observations will provide an important update to this record by measuring surface thermal emission at 9.4 cm with full surface dual polarization coverage for the first time from space, and comparison of this dataset with prior Magellan observations will aid assessment of how Venus’ surface changes over relatively short timescales.

In our presentation, we will review some important results from prior observations of Venus’ microwave brightness temperature spectrum, discuss new and ongoing observations from several observatories, and provide perspectives on what we can expect for VenSAR measurements. Some topics include:

- New observations of Venus’ disk-integrated spectrum from the CLASS observatory with absolute calibration precision < 3 K in the 1 millimeter – 1 centimeter wavelength range.
- Modeling of Venus’ emission spectrum and expected orders of magnitude of variability relevant to studies with VenSAR.
- Ongoing analysis of recent spatially resolved observations of Venus from several observatories over a wide wavelength range with a particular emphasis on observations sensitive to emission from the surface and subsurface (see figure below).



20 cm VLA observations over Aphrodite Terra in 1983 (left, Pettengill et al. 1988) and in 2021 (right)

Constraining the Lifetime of SO2 in the Atmosphere of Venus from a 1D Climate-chemistry Atmospheric Model

[1] Benjamin Taysum, [1] John Lee Grenfell, [1] Iris van Zelst, [1] Nils Müller, [1] Doris Breuer, [1] Ana-Catalina Plesa, [1,2,3] Heike Rauer

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Abstract

We develop a dry deposition submodule for the one-dimensional climate-chemistry coupled atmospheric model 1D-TERRA, and use it to simulate the steady-state composition of modern-day Venus. Prior to this work, atmospheric column models of terrestrial planets assume constant dry deposition velocity values for a select number of trace-gas species. These values are often set simply to tune the model results of trace-gas species to observational values. Our approach is a novel method that dynamically calculates the loss flux of each individual gas-phase species in the model to the planet surface, taking numerous atmospheric, meteorological, and surface-related parameters into account. Comparisons are made between the updated model, the previous "fixed" surface deposition version, and satellite observations. Then we use the updated model to estimate the atmospheric lifetime of sulfur dioxide (SO2) in the atmosphere of Venus based on the new approach that calculates variable deposition velocities. This allows us to provide constraints on the volcanic outgassing flux of sulfur species on Venus required to maintain the observed levels in the lower atmosphere (of the order of 100 parts per million). This new approach will enable more robust analyses of future SO2 measurements made by the EnVision orbiter and the DAVINCI atmospheric probe, as well as volcanic flux estimates from the VERITAS and EnVision spacecrafts, to be performed with our climate-chemistry atmosphere model.

HECATE Project: The Evolution of Venus: Coronae, Subsurface Structure and Volcano- Tectonics

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Abstract

The analysis of the Venusian geological record and in particular of coronae, one of the most puzzling volcano-tectonic features of our Solar System, holds pivotal clues to reconstruct the tectonic evolution of Venus and could reveal crucial information for understanding the planet's interior and its thermal evolution.

Here we present the HECATE project that proposes a multidisciplinary approach intertwining geological observations and mapping, statistical analytical procedures, and geodynamical modeling to address major scientific questions for the geological and geodynamical evolution of Venus. The project aims to collect observable geological evidence of the surface and use this to determine the structure of the shallow subsurface and further to constrain the dynamics of the deeper interior. HECATE will hence connect the different planetary layers (the surface, the shallow subsurface, and the deep interior) that are often addressed individually.

HECATE will be carried out in close collaboration between the hosting institution (University of Padova) and DLR (German Aerospace Center, Berlin) and will provide the first comprehensive, multidisciplinary, and well-rounded study on Venusian coronae, by producing high quality, accessible and reusable datasets of planetary mapping products, mechanical and rheological structure of the shallow subsurface, and geodynamical investigations with a strong focus on magmatic processes.

HECATE is a highly ambitious but timely project. The results obtained herein will provide valuable information to identify targets of interest for the future Venus missions, EnVision (ESA) and VERITAS (NASA), whose aims include the determination of the volcano-tectonic activity of Venus.

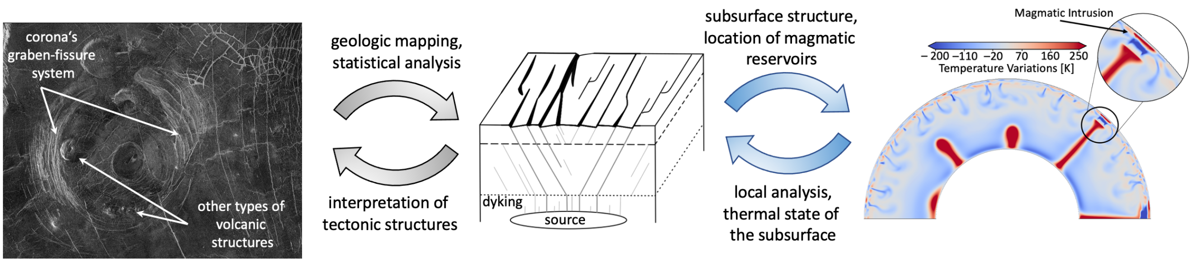

Figure 1:Investigations proposed by the HECATE project. The multidisciplinary approach adopted here includes geological observations and mapping, statistical analytical procedures, and geodynamical modeling.

Lithospheric and crustal thicknesses of geological provinces on Venus

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Abstract

The lateral variations of the crustal and lithospheric characteristics of Venus controlled by large geological provinces provides clues for the understanding of the geodynamical evolution of the planet. We have classified the data from the global models of crustal thickness, effective elastic lithospheric thickness and internal load fraction, from Jimenez-Díaz et al. (2015) (Icarus 260: 215-231) in geological categories. The global continuous models have been sampled through an equal-area dot distribution and classified using a global geological map. This procedure allows us to observe the mean crustal and lithospheric characteristics and the statistical data distribution for different geological categories including: Tessera dominated crustal plateaus, volcanic plains, volcanic rises, rift belts and Ishtar Terra. Significant differences between specific geological units in the same category can also be discerned, although the interpretation of the results remains controversial. This kind of mixed geological and geophysical analysis will be favoured when EnVision higher resolution topographic and gravity observations provide the basis for the new generation of more detailed models of crustal and lithospheric thicknesses. With the new models available, its classification though global geologic provinces will provide clues to understand the geodynamic behaviour of Venus.

The Basalt-Eclogite Phase Transition on Venus: Implications for Crustal Recycling and Partial Melting

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Abstract

On Venus, the transition to eclogite, characterised by the disappearance of plagioclase in favour of denser pyroxene and garnet, can play an important role for crustal delamination. This transition occurs when crustal material reaches pressures higher than 1.5 GPa, and since it is commonly associated with a negative buoyancy, it may limit the maximum crustal thickness. On Venus, crustal plateaus, whose composition might be similar to the continental crust on Earth [1] present some of the largest crustal thicknesses on the planet [2,3] and thus might undergo this transition. High surface heat flow estimations in these regions, however, could have led to localised melting before the eclogite transition occurred [3]. Here we use petrological models to calculate the depth of the eclogite transition for a variety of crustal compositions ranging from basalt to granodiorite. We use recent thermal gradient estimations of Venus's lithosphere [4,5,6] and calculate the mineral phase proportions and associated density profiles (Fig. 1). We focus on the density contrast between the eclogitic material and the underlying mantle to evaluate whether the conditions for crustal delamination are met. Furthermore, we test if melting occurs prior to the eclogite transition. Future measurements of the composition of crustal materials from VERITAS and EnVision combined with our investigation of the depth of the eclogite transition and its associated density will provide essential information to understand crustal delamination and melting on Venus.

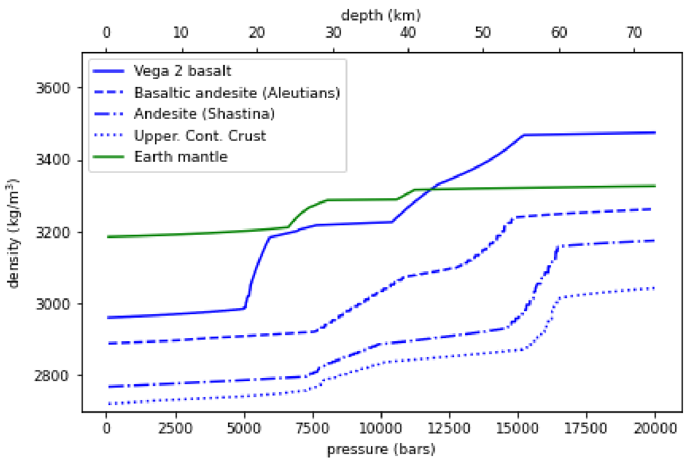

Figure 1: *Comparison between the density of the Vega 2 basalt, 3 more evolved terrestrial compositions and an Earth-like mantle along a thermal gradient of 5 K/km (surface temperature of 737 K). The basalt Vega 2 has a higher surface density and a higher density gain through the eclogite transition (500 kg/m³) compared to the progressively more evolved compositions (350–250 kg/m³). The Vega 2 basalt is the only composition that reaches negative buoyancy and could be recycled into the mantle. Calculations performed with Perple_X 6.9.1 and the HGP 2018 database [7].*

References: [1] Gilmore et al., 2015; [2] James et al., 2013; [3] Maia & Wieczorek, 2022; [4] Borelli et al., 2021; [5] Smrekar et al., 2022; [6] Bjonnes et al., 2021; [7] Holland et al., 2018.

LEAVES – DISTRIBUTED IN SITU SENSOR PLATFORM FOR GLOBAL ATMOSPHERIC DYNAMICS.

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Background and Overview: The current state of knowledge regarding the composition and dynamics of Venus' atmosphere, especially at the altitudes within and below the clouds, is based on limited descent profiles, remote sensing from orbital and terrestrial instruments, and computational climate models. Micro- and meso-scale processes responsible for chemical cycling, energy transport, and localized regions of (in)stability remain difficult to observe, model, and predict due to the paucity of direct measurements in the Venus lower cloud layers and deep atmosphere over a range of local solar times [1, 2]. Likewise, direct in-situ measurements of regions between 80 and 100 km have never been obtained from a descent probe, due to the physics governing the entry of conventional aeroshell-enclosed probes. LEAVES system design provides a mechanism for the acquisition of the first self-consistent measurement of Venus's upper atmosphere wind field and composition.

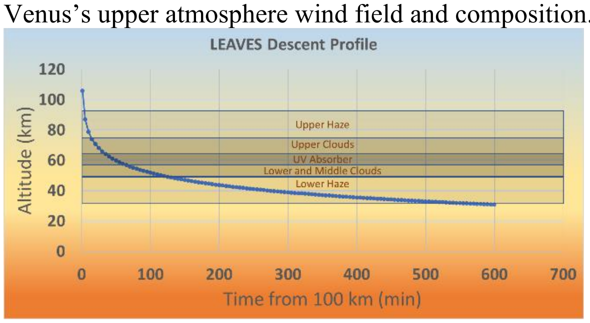

Figure 1. Comparison of the LEAVES' descent profile with regions of interest in the Venus atmosphere.

Repeated sequential deployments of the LEAVES platforms, separated by ~ 15° of latitude, from a series of unique local solar times provides a mechanism for coincident, multi-latitude, 100 to 30 km vertical wind and gas species profiles measurements. These measurements will provide unique and unprecedented insight into the micro- and meso-scale processes that influence Venus's global circulation patterns and climate [2].

Thus, LEAVES has the potential to provide the greatest and most detailed direct spatial mapping of the environmental conditions above, within and below the Venus cloud layers. As a result, any mission incorporating the LEAVES concept may serve as a pathfinder for the design of future longer-lived, cloud-dwelling aerial platforms, or, for example, missions to image the surface using aerial platform excursions below the clouds. Moreover, LEAVES would fully satisfy the first of three Objectives required for a New Frontiers VISE mission.

Entry Probe Concept: The LEAVES (Lofted Environmental and Atmospheric VEnus Sensors) is a novel architecture concept in which a very small electronics and sensor payload is integrated with an ultralight heat shield [Fig. 1], which provides protection from atmospheric interface heating, as well as a high-drag surface that provides an extended, unpowered dwelling time in the target altitudes of 30-100 km. The low, per-unit mass of <500 g combined with a projected surface area of 1.75 m^2 results in a low ballistic coefficient that enables direct deployment from orbit without further packaging. In contrast with traditional entry vehicles, LEAVES experiences peak deceleration and stresses at high altitudes of ~115 km above the surface. Thus, LEAVES data collection is able to commence at 100 km, well above Venus's upper clouds & haze [Fig. 2]. The data are collected by each of over 100 individual LEAVES units over a ~9 hour period, as the platform descends vertically and drifts laterally via the zonal wind flow.

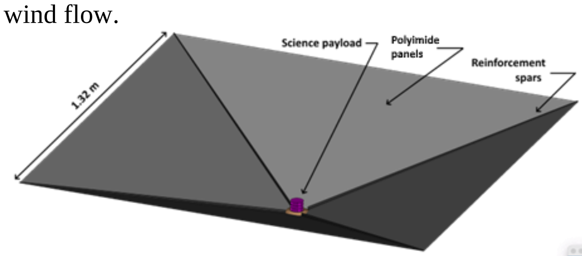

Figure 2. LEAVES structure, with quadralateral polyimide panels supported by four carbon-carbon fiber spars.

LEAVES Payload: Data acquisition is accomplished via a < 50 g payload in which communications, power, sensors (inertial measurement units, temperature, pressure, magnetometer, and two species-specific chemical sensors (SO_x and CO) [4, 5]) and data handling are integrated into a single, compact board [Fig. 3]. Prototyping work for both the flight structure and functional demonstration of the payload operations are ongoing.

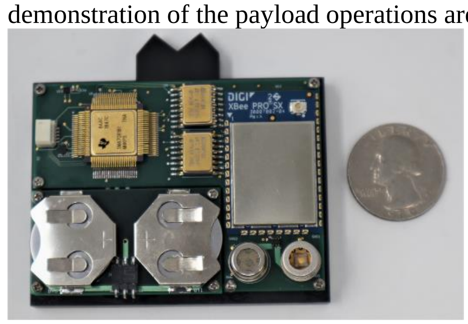

Figure 3. LEAVES sensor and electronic payload.

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Long-term Plan to Monitor Venus Using Earth-orbiting CubeSats

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Venus observations revealed considerable atmospheric variations over a long period of time. SO_2 gas abundance at the cloud-top level changed drastically over the past decade[1]. UV reflectivity controlled by the abundance of unknown absorbers in the upper clouds varied over the past decade[2]. Zonal winds at and below the cloud-top level varied over decades[3,4]. These findings imply the presence of yet hidden processes that affect the current climate on the planet. However, the nature of the reported variations remains unclear, e.g., sporadic or periodic, hampering the identification of possible processes. It may be associated with occasional volcanic eruptions[5], overlapped with impacts of the solar activity cycle[3,2], and possible dynamical oscillations in the atmosphere (e.g., a quasi-biennial oscillation existing in the Earth's atmosphere). To characterize the nature of the variability, continuous long-term monitoring is mandatory. And we are planning for such long-term monitoring using low-Earth orbit CubeSats to observe Venus over 10 years. The first CubeSat plan is being established under the confirmed funding by the Institute for Basic Science in South Korea for its first payload and the first CubeSat bus. Our CubeSat will acquire disk-integrated reflectivity of Venus at multi-wavelengths from UV to NIR in terms of total flux and the degree of linear polarization. We plan to launch the first CubeSat in 2026 and the other follow-up CubeSats after that date. The long period of observations by our CubeSats will overlap with the EnVision mission and other confirmed Venus missions (VERITAS and DAVINCI). Our CubeSat data will provide a long-term baseline to track the variability of Venus on a global scale. The data will quantify global impacts of surface volcanism if any, supporting the expected findings by EnVision and VERITAS, and impacts of solar activities (or cosmic rays). While the EnVision mission acquires excellent surface and atmospheric data at high spatial resolution, our CubeSat missions will obtain the time dimensional information, from hours to decennial time scales, crucial to investigate the climatology processes in the atmosphere.

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Observations of HDO and H_2O over Venus nightside by IRTF/iSHELL

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Abstract

Deuterium/hydrogen [D/H] ratio is a key diagnostic to understanding atmospheric evolution, such as water history. In the case of Venus, in order to measure the D/H ratio independently from the effects of atmospheric chemistry and formation of clouds, the D/H ratio deep into the atmosphere, i.e. below the thick clouds of Venus, should be measured. Previous high-resolution spectroscopic measurements by ground-based telescope revealed that the D/H ratio at the deep atmosphere of Venus (below clouds) is 150 times larger than the terrestrial standard (e.g., Donahue et al., 1982). The enriched deuterium on Venus can be interpreted either as the results of the atmospheric escape or continuous outgassing (e.g., Grinspoon, 1993), however the actual cause is still not understood. Since the last observations in the 1980s, no measurements of the D/H ratio in the Venus deep atmosphere have been reported. Furthermore, no spatial map of the D/H ratio has ever been investigated in the Venus deep atmosphere even though eruption of the (potential) current active volcanoes may decrease the D/H ratio on Venus by several tens of percent and could produce a spatial variation of D/H geologically correlated with volcanoes. On 11th February 2022, we performed high-resolution spectroscopy (R~75,000) of the 2.26-2.55 micron (K3 band) on the Venus night side with IRTF/iSHELL, which is able to measure both H_2O and HDO lines simultaneously the at the Venus deep atmosphere below the cloud layers (30-40 km altitude). Our observations aim to investigate spatially-resolved map of D/H ratio in the lower atmosphere. The observed iSHELL spectra will also be used to constrain further the expected performances of the VenSpec-H instrument, part of the EnVision mission payload. We will present and discuss the preliminary results.

A large Network of Medium and Small-size Telescopes Supporting EnVision

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Abstract

After the Moon, Venus is the brightest object of the night-sky. However, its observation from the ground faces significant challenges. The phases of the planet and its small separation from the Sun limits the coverage, time and quality of the observations that can be obtained from Earth. These difficulties also make Venus an unlikely target for most large space or ground-based telescopes. EnVision will observe Venus with an ambitious set of instruments at an unprecedented combination of spatial resolution and global coverage from a low orbit. It will study Venus as a coupled system from the interior and surface to the atmosphere and their mutual interactions. However, EnVision will not be able to simultaneously observe large portions of the dynamic atmosphere where to interpret the meteorological phenomena that it will investigate. In the last decade, the quality of observations of Venus obtained by amateur astronomers has increased considerably [1], resulting in studies of large atmospheric features [2-4] and in observations of the Venus surface at 1 μm [1]. The decreasing cost of SCMOS detectors sensitive up to 1.7 μm may allow some amateurs to take up the challenge to observe the lower clouds of Venus and atmospheric airglow at 1.27 μm with the equipment of the next decade. We propose to organize a large network of ground-based observations of the planet that will supply context images for EnVision. This network will have two research sides and a parallel outreach project: (1) High-frequency observations by coordinated amateur astronomers focusing in the dynamic atmosphere, but also observing the surface. (2) Calibrated observations obtained on 1-3.5 m telescopes by professional scientists including instruments such as the PlanetCam instrument [5] and others, addressing the variability of the atmosphere in both its dynamics and mean properties such as its albedo [6-7]. In parallel, a Citizen Science Outreach program based around the comparison of amateur, professional and Envision observations of Venus surface and atmosphere will communicate the excitement of Venus science to the public.

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Ground-based observations of $^{13}CO/^{12}CO$ in the Venusian atmosphere

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Abstract

One of the long-standing unsolved issues in the Venusian atmospheric chemistry is the stability of carbon dioxide (CO_2). CO_2 is photodissociated into carbon monoxide (CO) and oxygen by solar UV radiation. The direct recombination of the dissociated CO and oxygen into CO_2 (three-body reaction) is spin-forbidden, and therefore its efficiency is very low. In fact, if this were the only process to reproduce CO_2, all the Venusian CO_2 atmosphere would be dissociated within several tens of thousands of years. In reality, such a situation has not occurred. This means that there is some other reaction (catalytic reaction) that effectively restores CO_2 in the Venusian atmosphere. This problem has been raised by McElroy and Donahue in 1970's [1, 2], as was the case with the Martian atmosphere, but it is still not fully elucidated half a century later. Although chemical species of ClO_x and HO_x have been proposed as potential catalysts [e.g., 3, 4, 5], they have never been confirmed by observations. In practice it is almost impossible to detect such ultra-low concentrated species by remote sensing, and we have no choice but to wait for the realization of highly-precise in-situ measurements of atmospheric constituents by a future Venusian exploration.

In this study, we consider a different approach to this CO_2 stability issue by observing carbon isotopic fractionation in CO, $^{13}CO/^{12}CO$. Recent first-principles calculations by Schmidt et al. [6] indicated that, in the CO_2 photolysis, $^{12}CO_2$ is dissociated more rapidly than $^{13}CO_2$. In other words, the value of $^{13}CO/^{12}CO$ can become smaller than the standard CO isotopic ratio in a region where CO_2 photolysis is much active. The degree of the $^{13}CO/^{12}CO$ fractionation due to the CO_2 photolysis is suggested to be as significant as ~100 per mil. Such a fractionation has been confirmed in the Earth's mesosphere, and the latitudinal and vertical distribution of $^{13}CO/^{12}CO$ is successfully used as a tracer for CO formation and extinction [7]. We attempt to apply this approach to the Venusian atmosphere. The first step is to measure the $^{13}CO/^{12}CO$ value in high-spectral resolution spectra of Venus dayside obtained by IRTF/iSHELL. The outcome will be also useful in discussing the science objectives of the EnVision VenSpec-H observations.

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Structure of the Upper Atmosphere of Venus with Potential Applications to Upcoming Exploration Missions

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Abstract

The structure and composition of the upper atmosphere of Venus above 100 km is important for physico-chemical processes that couple to the lower atmosphere and for the aerobraking and entry, descent and landing (EDL) purposes. Thus a detailed knowledge of the upper atmosphere is essential to the interpretation of the measurements and the operation of the currently selected Venus missions, DAVINCI, VERITAS and EnVision, especially since none of them will directly sample the upper atmosphere. Previous observations by the SPICAV instrument on Venus Express reveal a wide range of possible temperatures and the likelihood of CO_2 condensation (Mahieux et al., 2015; Bhattacharya et al., 2022). The upper atmospheric temperature undergoes spatial and temporal variations resulting from regular and sporadic changes in the solar activity and dynamical processes. Global Ionosphere Thermosphere Model (GITM) for Venus provides the capability to resolve heat budget and dynamics of Venus upper atmosphere between 70-170 km at different conditions of solar activity (Ridley et al., 2006; Ponder et al., 2023). We present the temperature, pressure and mass densities corresponding to different solar activities from the above-mentioned non-hydrostatic GCM, resolving the ion-dynamics and chemical heating rates. It provides a better understanding of the state of the upper atmosphere with potential applications to the selected missions.

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Cloud simulation by a Venus MIROC GCM: The current status and future perspectives

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Abstract

The observation of the cloud and the related chemical cycle has a vital role in the Envision mission for a comprehension of the Venusian climate. Furthermore, measurement of volcanic gas is one of the most important targets of the EnVision mission. However, the observed intensity would be largely affected by the scattering of the cloud. Thus, modelling of the cloud structure and retrieval case study would be crucial to interpret the future observation. For this purpose, we are currently developing a 3-D Venus GCM that can simulate the cloud structure. We present a summary of a current 3-D cloud simulation (Karyu et al., 2023) and future perspectives.

In Karyu et al. (2023), we have implemented the processes of cloud condensation/evaporation, sedimentation, transport, and simple chemical reactions to maintain the H_2SO_4 cycle into the GCM. Cloud droplets are assumed to be composed of 75% weight fraction liquid H_2SO_4-H_2O, and their size distribution consists of Mode 1, 2, 2', and 3 based on the past in situ measurements (Knollenberg & Hunten, 1980). The dynamical settings of the GCM are based on Yamamoto et al. (2021), and thus, the dynamical and thermal structures are similar to the past GCM study.

The simulated zonal-mean cloud structure is in good agreement with past near-infrared measurements (Haus et al., 2014). The cloud top altitude is the highest at the equator and decreases towards the pole. Cloud mass loading is the largest in low and high latitudes and smallest in the middle latitudes. The cumulative optical depth variation in low latitudes ranged from 33 to 50, which is quantitatively consistent with the past observation (Haus et al., 2014). A substantial part of the variation is represented by a quasi-periodic planetary-scale variation coupled with an equatorial Kelvin wave, which is similar to cloud marking reported by Crisp et al. (1991). We found that the vertical wind associated with the Kelvin wave is essential for maintaining the quasi-periodic cloud variation.

Despite the successful reproduction of the Venusian cloud structure and variation, the model needs further development since the cloud parameterization is simplified and not necessarily based on microphysics. In doing so, the bin method used in past 1-D studies (e.g., Imamura and Hahimoto, 2001) is not feasible to be coupled with a GCM due to large computational cost. On the other hand, the moment method is computationally efficient and widely used in Earth studies (e.g., Mann et al., 2010). However, the moment method is yet to be validated under Venus conditions in a 1-D setting. Therefore, it is necessary to check the usability by comparing the moment method with the bin method before the coupling.

In this presentation, we are also planning to show the initial result of the moment method simulation in a 1-D setting and compare it with the bin-method simulation. In the next step, the further investigation of Venusian atmospheric sciences coupled with cloud microphysics is expected to be performed in a 3-D context after the implementation of the moment method into the GCM. The obtained size distribution or cloud structure in various atmospheric conditions should be important information for the future observation during the EnVision mission.

How Venus' core radius uncertainty affects mantle evolution and potential present-day observables

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Abstract

Despite the similarity in terms of radius and bulk density of Venus and Earth, the interior evolution of Venus is poorly understood, largely because of lacking data. As an example, the radius R_C of Venus core currently has an uncertainty of at least ±500 km. Core composition and thermochemical evolution may differ substantially for different end-member R_C, but the core radius also constrains mantle thickness D_M: with R_C = 3500±500 km for Venus, D_M = 2500±500 km. A thicker mantle features higher pressure and temperature and has different viscosity and heat transport properties than a thinner mantle. This affects the cooling history and with that the evolution of Venus' tectonic regime. The latter is only fragmentarily preserved in Venus' surface rocks and, therefore, no consensus has been reached about Venus' tectonic regime and how it has allowed for resurfacing through time.

As it will be shown with this work, not properly knowing the core radius complicates interpreting the already sparse observational record with respect to Venus' evolutionary pathway. Building on previous modelling studies, I compute a suite of whole-mantle evolution simulations for Venus conditions in a 2D spherical annulus geometry from 4.5 Ga until present-day, which include compressibility, mineral phase transitions, melting and crust formation. I vary the core radius and the yield strength of the lithosphere in this initial modelling suite. The main intention is to compute and compare potential present-day diagnostics for a spectrum of mantle thicknesses.

First results indicate that magmatic activity sets in earlier the smaller R_C, because at given initial core-mantle boundary (CMB) temperature, the thermal boundary layer between mantle and core is more unstable, promoting plumes. This implies faster growth of basaltic crust during the early evolution. For a given yield strength, the mantle and lithosphere may pass through different epochs featuring stagnant or sluggishly-mobile lithosphere during their long-term evolution. The relative timing of these epochs is different for variable R_C with consequences for potential present-day observables: with smaller R_C, the mantle cools globally faster, but the CMB temperature remains higher, potentially slowing down growth of a solid inner core. The higher mantle temperature with larger R_C enhances average present-day heat fluxes (R_C = 3000 km: 10 mW m^{-2} vs. R_C = 4000 km: 27 mW m^{-2}), but also increases melting and volcanic activity to promote crustal growth. However, the crust can still remain thinner, because the smaller upper mantle viscosity recycles of the crustal base more efficiently.

Overall, above initial results indicate some meaning trends for interpreting current and future data with respect to Venus' temporal evolution. I will present a more systematic investigation using different lithospheric yield strength profiles and mantle viscosities. Future EnVision data for pinning down Venus' core radius more precisely could eliminate substantial parts of the here-discussed issues.

The Tectonics and Volcanism of Venus: New Modes Facilitated by Realistic Crustal Rheology and Intrusive Magmatism

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Abstract

The young surface age and absence of plate tectonics on Venus have led to the proposal of two tectonic models: an episodic-lid regime with global lithospheric overturns, or an equilibrium resurfacing regime with numerous volcanic and tectonic activities. However, stratigraphic analysis suggests that Venus' surface tectonics could be a combination of these two end-member models with a global resurfacing event that created most of the crust, followed by tectonic and volcanic activities until now.

In this study, we present a series of global 2-D thermochemical convection models (using StagYY) to investigate the tectonics and mantle evolution of Venus. Our models consider realistic parameters, including a composite rheology (dislocation creep, diffusion creep, and plastic yielding), intrusive magmatism, and experiment-based plagioclase (An_{75}) crustal rheology. We find that surface tectonics is strongly affected by crustal rheology. Models with a "weak" plagioclase-rheology crust exhibit episodic overturns but with continuously high surface mobility and high distributed surface strain rates between overturns, leading to a new tectonic regime that we name "deformable episodic lid." Internally, the composition-dependent density profile applied in our models generates a "basalt barrier" at the mantle transition zone, which has a significant impact on Venus' mantle evolution. Only strong plumes can penetrate this basalt barrier and cause global lithospheric overturns. This basalt barrier also causes global internal episodic overturns that generate global volcanic resurfacing in stagnant-lid models. This suggests a new resurfacing mechanism that we name "stagnant episodic-volcanic-resurfacing," which does not involve lithospheric overturns.

Both the model assumptions (e.g. crustal rheology) and model output (crustal thickness, eruption/outgassing rates, surface heat flux) can be compared to observations to be obtained by Envision, as the instruments will provide high-resolution surface mapping, gravity measurements, and spectral data (VenSpec suite: volcanic outgassing, surface composition and hot spots) on Venus. Therefore, the combination of the model simulations and observational data from EnVision will provide a more complete understanding of the tectonic regime and mantle evolution of Venus.

Influence of Possible Interior Structures on the Long-Term Evolution and Outgassing of Venus

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Abstract

Venus' mass and radius are similar to those of Earth. However, its interior structure and chemical composition are poorly constrained. Seemingly small deviations from the Earth might have important impacts in the long-term evolution and dynamics of Venus when compared to our planet and could help in explaining the different present-day surface and atmospheric conditions and geophysical activity between these two planets. *Shah et al*. (ApJ 2022) presented a range of possible bulk compositions and internal structures for Venus. The models, that are designed to fit Venus' moment of inertia and total mass predict core radii that are ranging from 2930-4350 km and include significant variations in mantle and core compositions. In this study, we pick ten different Venus models from *Shah et al.* (ApJ 2022) that range from a small to a big, and from a S-free to a S-rich core. We run mantle convection evolution models for the different scenarios using the code StagYY (*Tackley, PEPI 2008; Armann and Tackley, JGR 2012*) and explore how different interior structures and chemical compositions affect the long-term evolution and dynamics of Venus. Specifically, we investigate how the composition and size of the core affects magmatism hence outgassing of water and other volatiles to the atmosphere, the basalt distribution, heat flow and temperature of the mantle and lithosphere. Since the tectonic regime active on Venus is still unknown, we test different evolution scenarios for a planet covered by a stagnant lid, an episodic lid, and a plutonic-squishy lid. The models produce a range of predictions that can be compared to planned EnVision measurements by the VenSpec spectrometers, including outgassing of water and other volatiles and surface composition. These can be used to constrain Venus' interior composition and structure, and reveal key information on the differences between Earth and Venus.

Numerical studies on polysulfur in Venus' atmosphere

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Abstract

Polysulfur, sulfur oxides, and chlorosulfanes on Venus have been the subject of multiple recent studies (e.g., Francés-Monerris et al, Nature Comm 13:4425, 2022; Adams et al, LPSC 1533, 2022; Pinto et al, Nature Comm 12:175, 2021; Mills et al, COSPAR B4.4-0012-21, 2021; Frandsen et al, J Ph Ch A 124:7047, 2020; Bierson and Zhang, JGR Planets 125:e2019JE006159, 2019; Mills and Allen, Plan Sp Sci 55:1729, 2007). Key observed features that have been the focus for these studies are the identity of the UV-visible absorber which accounts for around 50% of the sunlight absorbed by Venus' atmosphere and the presence of an SO_2 inversion layer in Venus' mesosphere.

Production of polysulfur leading to S_8 can proceed via direct association reactions or potentially via pathways involving chlorosulfanes (Mills and Allen, 2007), $(SO)_2$ (Pinto et al., 2021), and/or S_xO (Pinto et al., 2021; Francés-Monerris et al, 2022), as illustrated in Fig. 1. Rates for some sulfur association reactions ($2S+M \rightarrow S_2+M$, $S+S_2+M \rightarrow S_3+M$, and $2S_2+M \rightarrow S_4+M$), key reactions involving chlorosulfanes, and reactions involving $(SO)_2$, S_2O, ClS, and ClS_2O have been studied in the laboratory or computationally (e.g., Murrells, J Chem Soc Faraday Trans II 84:67, 1988; Murrells et al, J Chem Soc Faraday Trans II 84:85, 1988; Lu et al, J Chem Phys 125:164329, 2006; Du et al, J Chem Phys 134:154508, 2011; Frandsen et al, 2020; Francés-Monerris et al, 2022). Rates for other sulfur association reactions have been estimated based on these (e.g., Moses et al, Icarus 56:76, 2002). Significant uncertainties remain regarding the primary pathways for production of S_x and the potential impacts of these pathways on the abundance of sulfur species in Venus' upper mesosphere. These questions will be examined in this presentation.

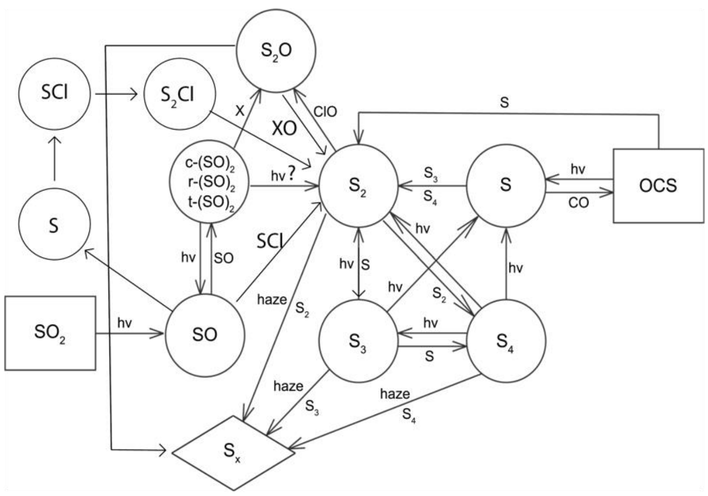

Figure 1. Schematic diagram showing the main routes for producing Sx from SO2 and OCS in Mills and Allen (2007), Pinto et al (2022), and Francés-Monerris et al (2022). After Pinto et al (2021).

Constraining the Interior Structure of Venus from the Gravitational Response to the Atmospheric Loading

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Abstract

The gravity field of Venus is periodically perturbed by the redistribution of mass induced by the atmospheric dynamics. The main contribution to the atmospheric time-varying field is given by the planetary scale thermal tides that generate a large mass transportation induced by solar heating. The atmospheric pressure loading exerted on the surface deforms the solid planet generating a gravitational response. The magnitude of this effect depends on the properties of the interior structure of the planet, and it is parameterized by the load Love numbers. We show here that measurements of these coefficients through the detection of the gravitational response to the atmospheric loading in the radio science data can provide additional constraints on the interior structure of Venus. By using the Venus PCM (formerly IPSL Venus GCM), we simulate the atmospheric dynamics of Venus and its gravitational effects, including the thermal tides and other planetary and small-scale waves. To constrain the contribution of the internal structure to the atmospheric gravity field, we computed ensembles of interior models by accounting for different properties of the mantle and core. We show that the detection of the gravitational response to the atmospheric loading provide information on the state and the size of the planetary core. Furthermore, the combination of the load Love numbers with the tidal Love numbers constrains the viscosity and the thermal state of the mantle. This study is relevant to the ESA EnVision mission, which will conduct geophysical investigations at Venus with the aim of better understanding its interior structure and thermal evolution. We will explore the possibility of measuring the gravitational response to the atmospheric loading with the EnVision radio science investigation.

New Venus Atmospheric profiles derived from Magellan Radio Occultations

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Radio occultation (RO) is a well-established technique that has been used by multiple planetary spacecraft to characterize planetary neutral atmospheres and ionospheres. In the case of Venus, radio occultation is the only spacecraft remote sensing technique that allows the derivation of atmospheric physical parameters below its thick cloud layer with the highest vertical resolution. Moreover, through the analysis of the amplitude of the radio signal, this technique enables the characterization of the concentration of the main component (sulfuric acid) in the clouds that enshroud the planet. The formation of the dense and extended sulfuric acid cloud layers, is a key feature of study in the efforts to understand and characterize Venus' atmosphere as a coupled chemical, radiative and dynamical system. Although, there has been found a reasonable agreement between the model predictions and measurements of the sulfuric acid vapor abundances through radio occultation observations in the middle and upper cloud layers, this is not the case for the lower cloud layer. Given that the lower cloud layer has the highest concentration of sulfuric acid vapor, it is essential to resolve these apparent conflicts.

Despite the fact that there is an ample set of raw spacecraft signal recordings available from multiple past Venus spacecraft, only a small subset has been analyzed from which density, temperature, pressure and sulfuric acid abundance profiles have been derived. Our team is currently in the process of analyzing NASA's Magellan datasets between 1991 and 1994. Our work will be used to update the Venus International Atmosphere (VIRA) model, which in addition to ESA's Venus Express (VEX) and JAXA's Akatsuki radio occultation data, will enable the analysis of the temporal variation of these profiles over multiple decades, with an extended coverage of spatial and solar illumination conditions.

Effects and detectability of a possible near-surface particulate layer from EnVision/VenSpec-M observations

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Abstract

In 1982, Venera 13 and 14 descent probes recorded the internal radiation field from an altitude of 62 km down to the surface, over a wavelength range of 0.48 to 1.14 µm. The originally recorded data was lost [1], fortunately, a secondary dataset was created by digitizing the graphic material published earlier. While analysing this dataset, [2] reported a rapid change in radiances indicative of a near-surface particulate layer. The presence of such a layer could be indicative of aeolian or condensing species; furthermore, it could affect the viability of surface imaging from future in-situ missions. It could also affect the nightside thermal emission from the surface and the deep atmosphere as observed from a spacecraft. The VenSpec-M will perform such observations in several surface-observing spectral windows from 0.78 to 1.18 µm [3]. Motivated by the EnVision and other upcoming Venus missions, we re-analyse the Venera 13 and 14 spectroscopic datasets to learn more about a possible near-surface particulate layer, its effects on the near-IR observations, and its detectability.

We use NEMESIS [4], a radiative transfer and retrieval tool, to retrieve the particle abundances for a range of possible size distributions of a hypothetical near-surface particulate layer. Next, using the retrieved near-surface particulate data, we perform simulations of the nightside thermal emission from 0.78 to 1.18 µm. The change in the observed radiances with respect to an assumed variability of the near-surface particulate layer is investigated. Several parameters affect the accurate modelling of the nightside near-IR spectra, including the collision-induced absorption coefficient of CO_2, surface temperature and emissivity, the optical thickness of the main cloud deck, etc. Considering the variations of these parameters, we discuss in this work, if it would be possible to detect the presence of a near-surface particulate layer from the near-IR spacecraft observations.

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Session 6: Communicating the EnVision story – oral talks

Venus: new perspectives towards 2031

Communicating the EnVision story: plenary discussion

[1]Lily Hibberd, [2]Annick Bureaud, [3]Sarah Kenderdine

[1] Université Paris Cité, [2] Leonardo/Olats, [3] École polytechnique fédérale de Lausanne

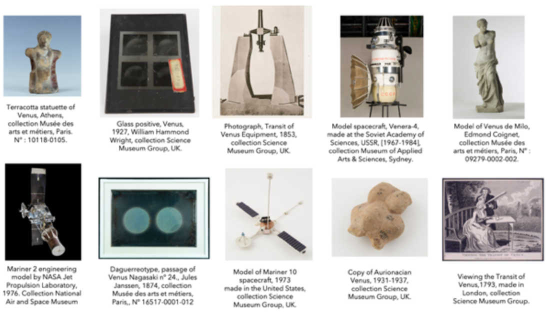
Detail from “Venus: Didilia Corona”, 2022, oil on board.

I am an Australian-born artist who develops long-term creative research and collaboration with communities, artists, scientists and historians, presented in 47 major Australian and international museums and festivals since 1997[1]. My practice combines performance, writing, painting, photography, video and installation art, and is grounded in significant scientific content and contexts, including collaborations with major European institutions such as Paris Observatory. “Venus: new perspectives towards 2031” is a collaborative creative project centred on the Earth's twin planet. There are four entwined branches to the project, which I propose to develop with my co-authors in the context of the ESA-NASA EnVision mission:

1. An ongoing study in oil paint of 100s of sites on Venus that interrogate and enliven the synthetic aperture radar (SAR) images from NASA's Mariner 10 and Messenger Venus space probes of 1974 and 2007. Fifty of these works were presented as a three-screen video installation in the recent exhibit in Switzerland titled *Cosmos Archaeology*.

Cosmos Archaeology: Explorations in Time and Space
EPFL Pavilions in Lausanne, Switzerland, curated by EPFL Profs. Sarah Kenderdine and Jean-Paul Kneib. Photos: Julien Gremaud

2. Creating new visualisation, museological and art-science approaches to engage diverse publics and specialists in reimagining Venus. Project outcomes will also provide the basis for exhibitions, events, and scientific, creative or promotional publications in the lead up to 2031. Confirmed collaborating co-authors include Prof. Sarah Kenderdine, EPFL Laboratory for Experimental Museology, and Paris-based art and technoscience curator and critic Annick Bureaud director, Leonardo/OLATS.[2]



Left: Venus artefacts from around the world. Right: *The Dynamic Universe*, EPFL Laboratory for Experimental Museology & EPFL LASTRO.

3. Archival research to assemble all the known artefacts related to Venus, encompassing cultural/anthropological collections from all over the world, space science instrumentation, early astronomical imaging and observational instruments and different radar datasets. This work will also forge collaboration and outreach opportunities with major international museums including the Science Museum (UK), Musée des arts et métiers (FR), and others.

4. It is often overlooked that almost every human society tells a unique gendered story through Venus. My collaborators and I therefore hope to support the EnVision project to propose outreach products and general interaction with a wider public in Europe and in the United States. This effort will be focused on the exploration of Venus as an archive of human civilisation. Combining points 1–3 above, we will explore and visualise geological features of Venus and their IAU names celebrating female writers, artists and scientists, or mythological figures and names attributed to Venus from diverse cultures all over the world.

[1] www.lilyhibberd.com

[2] https://www.epfl.ch/labs/emplus/ & https://www.olats.org

Solar system 3D viewer for outreach in space exploration missions: Application to EnVision

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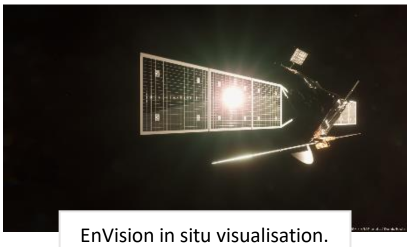
Abstract

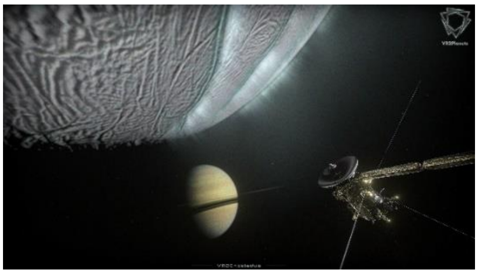
VR2Planets is a French company specialized in the integration of data from space exploration missions. The company creates virtual environments to visualize and interact with data acquired by probes from orbits to ground for all types of planetary environments. Our customers are research laboratories, universities, and national and international space agencies.

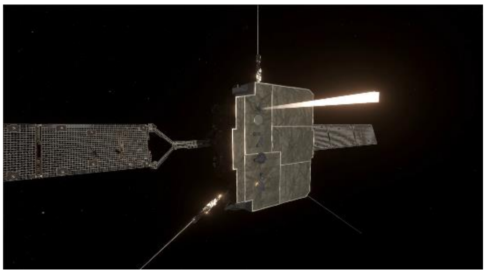


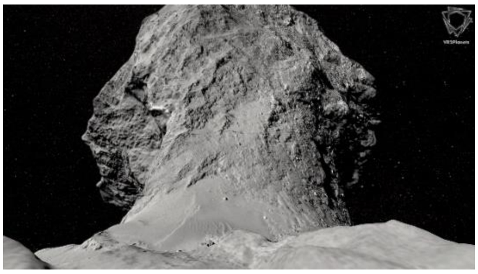
EnVision in situ visualisation.

1. Graphical content

VR2Planets was commissioned to create virtual environments to highlight the data acquired by different space missions on very different planetary environments. The topics of the virtual environments created can be missions, instruments, or acquisition processes. All software produced requires viewing content whose quality has made the company's reputation. The Figures below shows examples of realizations directly extracted from our virtual environments without digital retouching (from left to right: Cassini around Enceladus, Solar Orbiter around the sun and OSIRIS data from Rosetta on the comet Tchouryoumov-Gerasmienko). Spacecrafts and rendering of planetary terrains are realized by our graphical services.







2. Scientific content

The software developed by VR2Planets presents different types of scientific content:

- All planetary environments created by VR2Planets interface with standard orbitography data exchange formats (SPICE kernels, NASA/NAIF) providing real position and rotation of each natural and artificial bodies in the solar system at any time.
- Knowing the internal characteristics of the instruments (contained in the SPICE kernels) we can visualize the fields of view of the sensors and project the acquired data directly onto their acquisition site.
- The processes for acquiring data and deploying probes are reproduced identically (see below, from left to right: ACS occultation onboard TGO, SAR acquisition on Cassini, SEIS deployment on Insight)