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THE VENSPEC-U UV IMAGING SPECTROMETER ABOARD THE ENVISION MISSION: MODES OF OPERATION AND EXPECTED SCIENCE

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Abstract. The VenSpec-U (also called VeSUV) project is part of the EnVision mission as a core element of the VenSpec instrumental suite. The VenSpec-U science objectives are dedicated to monitoring the cloud top abundances of volcanic sulphur gases (SO, SO_2) as well as UV contrasts through spectral and spatial analysis of scattered 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 dual channel UV imaging spectrometer. As a main French instrumental contribution, the EnVision SNO has been labelled for the supervision of the instrumental development, operation, data acquisition, processing and archiving.

Keywords: Venus, UV spectrometer, EnVision, VenSpec

1 Introduction

ESA's Cosmic Vision M5 EnVision mission to Venus will be launched in December 2031 and begin its scientific mission in 2034 for a nominal duration of four years. Its payload includes the VenSpec spectroscopy suite with the VenSpec-M (Helbert et al. 2019), VenSpec-H (Robert et al. 2024), VenSpec-U and a Common Central Unit (CCU) (Wolff et al. 2024). The ultraviolet spectro-imager VenSpec-U is designed and manufactured by a consortium of French laboratories (LATMOS, IRAP, and LIRA) (Marcq et al. 2021) with scientific objectives dedicated to mapping sulfur gases at the top of the planet clouds, and characterizing the clouds variability, particularly that of the UV absorber, the nature of which is still undetermined to this day (Titov et al. 2018).

2 Instrument technical description

VenSpec-U is a compact ultraviolet spectrometer developed for ESA's EnVision mission to Venus, inspired by the UV spectrometers SPICAV-UV on Venus Express (Bertaux et al. 2007) and PHEBUS on BepiColombo (Quémerais et al. 2020). It integrates an optical box (Obox) and an electronic box (Ebox) to minimize mass and size, though at the cost of increased mechanical and thermal complexity. The enveloppe of the instrument is $291 \times 468 \times 353$ mm^3 for a total mass of 9.32 kg. The instrument is mounted and conductively coupled to the spacecraft in a thermally stable cavity.

In order to meet its science objectives, VenSpec-U features a dual-channel system for low (LR) and high (HR) spectral resolution, using a single CMOS detector. The channels are co-aligned and operated simultaneously, utilizing a rolling shutter scheme. Each channel has a baffle, lens objective system, and a spectrometer with a holographic grating and short-pass filters to remove wavelengths beyond specified ranges. A light trap reduces

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stray light. Technical characteristics of the instrument are summarized in Table 1 and Fig. 1 (Lustrement et al. 2024). The Signal-to-Noise Ratio (SNR) of the instrument was confirmed by a sensitivity study based on radiative transfer models (Conan et al. 2024).

Calibration is performed by solar observations using optical diffusers and pinholes during specific spacecraft maneuvers once every 3 months. The wheel mechanism also handles the opening and closing of optical apertures for observations, calibrations, and contamination protection. The detector temperature is regulated to -25°C with a Peltier cooler linked to the spacecraft thermal interface. UV LEDs in the Obox provide homogeneous irradiance for functional tests and sensor characterization. The design is focused on cleanliness to prevent contamination, which could degrade UV performance. Anti-contamination heaters prevent material buildup, while decontamination heaters clean optical surfaces as needed. The horizontal resolution will be around 10 km, to constrain the interactions between photochemistry and atmospheric dynamics on small scales such as gravity waves or convection cells (Marcq et al. 2021; Lefevre et al. 2024).

Table 1. Table summarizing the technical characteristics of the VenSpecU spectrometer.

	spectral range	**spectral resolution**	**Transverse iFOV**	**SNR at 220 nm**
HR	205-235 nm	0.3 nm	20 (°)	≥ 100
LR	190-380 nm	2-5 nm	20 (°)	≥ 200

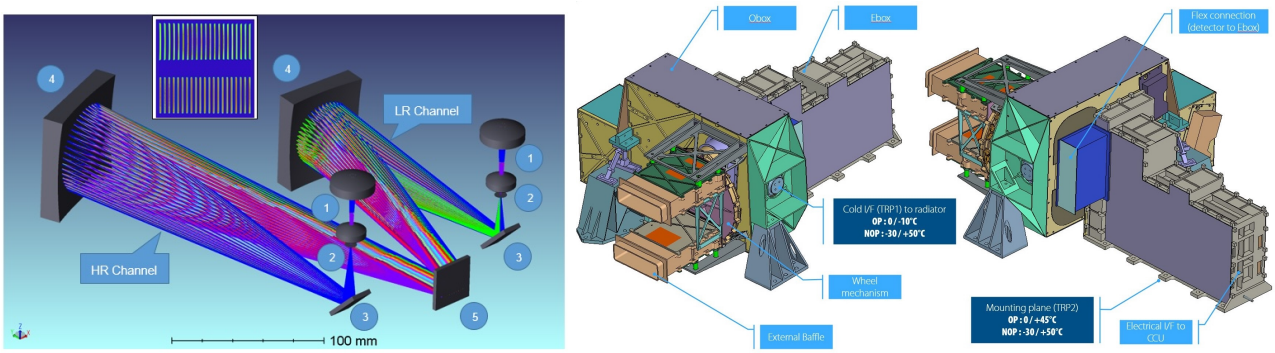

Fig. 1. Left: Optical description of the two channels of VenSpec-U comprising: (1-2) entry objectives, (3) visible rejection filters, (4) toroidal gratings, (5) common CMOS detector. **Right:** mechanical structure of the instrument.

3 Operation modes

3.1 Venus observations

The Envision spacecraft will be placed on a low quasi-polar Venus orbit ($87° < i < 89°$). Its altitude will range from 220 to 540 km for an orbital period of about 92 min. These observations will be performed in a pushbroom geometry: both slits (for LR and HR) will have their spatial axis perpendicular to the orbital swath (cross-track), which will provide the second (along-track) spatial dimension. A typical observation of Venus by VenSpec-U during a half-orbit, on day side, will therefore consist first in a preparation phase which will occur on night side preceding the observation (instrument switch, configuration, acquisiton of dark frames, wheel mechanism aperture). The acquisition parameters (binning scheme, stacking, etc.) can be updated several times during the observation to adapt to observing conditions and resolution requirements. Data are acquired and processed on the fly then sent to the VenSpec CCU for compression. After the observation is completed, the instrument is reconfigured (detector is warmed up, wheel is closed) and switched off until the next observation opportunity.

3.2 Solar calibrations

VenSpec-U will have some opportunities during the mission to perform radiometric calibration on the Sun. This will be achieved by off-pointing the spacecraft every 112 days such that the Sun crosses the instrument FoV. The radiometric calibration will rely on the combination of mainly two Sun scans. The first scan will use a set of pinholes providing the radiometric calibration for a small portion of the FoV. The pinholes are not affected by molecular contamination so the quality of this calibration method is expected to be very stable during the mission. The second scan will use a set of diffusers which may be affected by molecular contamination, but will enable calibration of the full FoV. Occasionally, a third scan will be requested to perform a calibration with another set of diffusers ("reference diffusers"). These diffusers are expected to contaminate much slowly than the nominal ones, thus enabling a relative tracking of the contamination.

3.3 Dark and internal calibrations

The calibration plan also foresees dedicated sessions to characterize and track any evolution of the dark current of the CMOS sensor. This will be done periodically for different sets of parameters such that the collected data will feed a dark current model used to support the inversion pipeline. The internal calibration, using the UV sources, will be used to perform in-flight PTC (Photon Transfer Curve), PRNU (Pixel Response Non Uniformity) characterization and diagnosis of the CMOS sensor.

4 Science objectives

4.1 Map SO_2 above the clouds of Venus

The variability of sulfur dioxide (SO_2) above the clouds of Venus has been observed since the 1980s, showing significant fluctuations over time. Data from space missions such as Pioneer Venus Orbiter and Venus Express, as well as Earth-based observations, indicate that SO_2 levels at lower latitudes can vary dramatically, spanning three orders of magnitude (Encrenaz et al. 2012; Wilson et al. 2024). In contrast, high-latitude regions beyond $\pm 50^\circ$ show much lower SO_2 levels. Most of the variability at lower latitudes is due to transient SO_2 "plumes" that are localized (less than 1000 km wide) and short-lived (lasting a few Earth days).

The rapid changes in SO_2 levels suggest a short atmospheric lifetime for SO_2, likely due to fast photochemical reactions. The supply of SO_2 from the lower atmosphere to the cloud tops is dependent on deep vertical mixing, which varies with time, location, and external factors such as volcanic activity. Further observations are needed to understand the mechanisms driving these variations.

4.2 Map SO:SO_2 ratio

As mentioned previously, the primary sink for SO_2 above the clouds of Venus involves its dissociation by UV sunlight: $SO_2 + h\nu \rightarrow SO + O$. To better understand the sulfur chemistry, it is crucial to measure the SO:SO_2 abundance ratio. However, the SO absorption spectrum overlaps with the stronger SO_2 absorption band around 220 nm, requiring high spectral resolution to distinguish between the two.

Observations using the STIS UV spectrograph on the Hubble Space Telescope found a column abundance ratio of SO:SO_2 averaging 1:10, ranging from 1:4 to 1:25 (Jessup et al. 2015). These measurements are limited due to their sparsity and large error margins (over 50%), making it difficult to determine any correlation with other parameters. Furthermore, colocated SO_2 and SO measurements could reduce uncertainties in SO_2 UV data retrievals, as many studies assumed a constant SO:SO_2 ratio of 1:10, which may not account for its actual variability.

4.3 Long-term monitoring of UV absorber

The upper clouds of Venus are known to contain an unidentified species (or several species) that absorbs in the blue and near UV range, peaking around 365 nm. Despite various candidates like $FeCl_3$ and OSSO being proposed, the exact composition remains unknown to this day (Egan et al. 2025).

The UV absorbing areas at 365 nm are longer-lived than sulfur species such as SO and SO_2, persisting beyond the 4-day cloud top superrotation period. This makes them useful for wind speed measurements through "cloud tracking", assuming comparatively slow microphysical processes like condensation and evaporation. The spatial contrasts of these UV absorbers have revealed sub-solar convection cells and atmospheric waves (Titov et al.

2018). Another significant interest in this UV absorber is its long-term variability. Since many orbiters, like Venus Express and Akatsuki, and Earth-based observations have monitored Venus at 365 nm, a decennial variability in albedo up by 20 points in reflectance has been observed. Understanding the causes of these variations and their potential connections to other variables, such as SO_2 abundance or wind speeds, is crucial for understanding Venus' climate and its evolution (Lee et al. 2019).

4.4 Small spatial scale studies

At the cloud top level of Venus, numerous dynamic structures have been observed in the 365 nm absorption band of the unknown UV absorber. The VMC instrument on Venus Express detected convective-like structures near the subsolar point extending about 20 km across. Linear wave fronts with wavelengths of 3 to 21 km were also observed, mainly above high surface elevations (Piccialli et al. 2014). These observations suggest a coupling between topography and atmospheric circulation at the cloud tops, later confirmed by thermal infrared observations from Akatsuki.

The presence of small-scale spatial contrasts in the UV absorber raises questions about similar variations in other parameters at the cloud top, such as SO_2 and SO column densities and cloud top altitude. These observations are valuable for improving large eddy or mesoscale simulations that model small-scale dynamics and local processes, like photochemistry or microphysics. Current models rely on assumptions (e.g., boundary conditions, chemical reactions, microphysical processes) that remain poorly understood as of today.

5 **Envision** *Service National d'Observation*

The French contribution to the EnVision mission is spread over several instruments and/or experiments: scientific responsibility and providing the UV spectral imager VenSpec-U; providing the optical subsystem of the IR imager VenSpec-M; scientific responsibility and pipeline development for the radioscience experiment. The proposed spectrometers cover wavelengths ranging from UV to infrared and will be used to detect temporal variations in surface temperature as well as in the concentration of volcanic gases in the atmosphere. These measurements will also make it possible to study interactions between the planet surface and atmosphere. Radio science measurements will provide information on the vertical density of Venus' atmosphere, the sulfuric acid content of the clouds (via radio occultations), as well as the internal structure of the planet through its gravity field (size and state of the core, mantle viscosity, crust and lithosphere structure).

These contributions are coordinated at the national level through a *Service National d'Observation* (SNO) during all phases, from their design and instrumental development (ongoing activities) to the development of the data processing pipeline and eventual archiving in the ESA Planetary Science Archive.

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