The Venus Emissivity Mapper (VEM): Instrument design and development for VERITAS and EnVision

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ABSTRACT

We report on the current Venus Emissivity Mapper (VEM) instrument design and development status onboard NASAs Venus Emissivity, Radio science, InSAR, Topography, And Spectroscopy (VERITAS) and ESAs EnVision orbiters. The VEM instrument is a push broom multispectral imager that comprises an optical system based on a sophisticated filter assembly with 14 spectral bands and an InGaAs detector with integrated thermoelectric cooler. A turn window mechanism and a two-staged baffle in front of the optics protect the instrument against contamination and straylight. The instruments nominal mass is approximately 6 kg. VEM opens the path for mapping Venus surface emission with a global coverage of >70%.

Keywords: VERITAS, VEM, EnVision, VenSpec-M, Venus, N-IR, SWIR, InGaAs

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1. INTRODUCTION

The two orbiter missions Venus Emissivity, Radio science, InSAR, Topography, And Spectroscopy (VERITAS) led by NASA and EnVision led by ESA are dedicated to investigate the geological evolution and current state of our neighbor planet Venus, including its relationship with the atmosphere [1−3]. In recent decades, it was assumed the composition of the Venus surface could only be studied by lander missions, because of the planet's strong atmospheric distinction and permanent cloud cover present in the visible spectral range. However, as has been demonstrated by the VIRTIS instrument on ESAs Venus Express mission, the Venus atmosphere provides narrow transparent spectral windows in the near-infrared spectral region around 1 µm, a highly informative region for geological features including iron-bearing minerals [4, 5]. The Venus Emissivity Mapper (VEM), on EnVision called VenSpec-M, is a scientific payload instrument onboard the VERITAS and EnVision orbiter missions and builds on these recent successes. VEM will be the first flight instrument which allows for mapping of the Venus surface emission on a global scale, with a coverage of >70% [6−8]. This is realized by observing the surface from orbit through six narrow band optical filters, ranging from 0.86 to 1.18 µm. Eight further optical filter channels will be used to provide information on water vapor abundance and cloud microphysics, which allows for correction of atmospheric effects. First VEM mission data is expected in the 2030s and will provide key insights in the divergent evolution of Venus.

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2. INSTRUMENT DESIGN AND DEVELOPMENT APPROACH

The VEM instrument is a multispectral push broom imager, operating in the near-infrared spectral region from 790 to 1510 nm. A picture of the current VEM design is shown in Figure 1. The instrument architecture comprises an electronic box including power supply and instrument controller unit. The latter is based on a Ng-medium FPGA (NanoXplore) including a 32-bit CPU (LEON-FT) to process the VEM science and housekeeping data. The image processing will include several operations, e.g. digital time delay integration (TDI), macro-pixel binning and compression. The whole electronic box serves as the instruments main structure and mechanical mounting interface, including first thermal reference point (TRP1), to the spacecraft (S/C). It also provides the main and redundant power and data handling (SpaceWire) interface connectors.

The telecentric VEM optics subsystem (VEMO) is mounted on top of the electronic box. VEMO is a contribution from CNES. It consists of an opto-mechanical tube covering three lenses and a sophisticated multilayered, narrow band filter assembly. The design and assembly integration and verification (AIV) of VEMO is subcontracted and under the responsibility of LESIA. The filter assembly inside VEMO is managed by CNES, while the design, manufacturing and AIV is provided by Bertin Winlight with the individual filter stripes being coated and designed by CILAS. The scene, typically taken from the Venus nightside, is focused by the VEMO entrance telescope lens onto the filter array, that splits the signal into 14 individual spectral bands with different central wavelength (CWL) and bandwidth. The filters cover the atmospheric spectral windows mentioned previously as well as some spectral regions used to characterize the impact of water and clouds on the spectra acquired. Figure 2 shows a typical transmission spectrum as it can be expected for the 14 filter stripes within the VEM wavelength range including their current filter number, which corresponds to the physical position on the filter assembly, and CWL. The Venus surface emissions through the atmospheric windows are covered by six surface filter bands (4,7,8,10,11,12). Atmospheric effects are captured by two water filter bands (3,6) and three cloud filter bands (1,13,14). Three additional filter bands (2,5,9) are dedicated to measure the background with a well-chosen CWL placed in regions of the emission spectrum where no signal from Venus is expected.

In order to minimize the incidence effect with the interferential filters, the VEMO entrance lens must be telecentric on the filter assembly. With telecentricity, all beams on the filters are cones with null average incidence. Consequently, the two-lens relay optics located behind the filter assembly needs to accept telecentric beams on the object side and has to focus the image onto the detector focal plane. With the relay optics, the radiation transmitted through the filter assembly is mapped on smaller spatial scales compared to the image in the telescope focal plane (magnification factor < 1). The effective f-number of VEMO, i.e. at the relay optics focal plane (position of the detector) is then smaller than at the telescope focal plane (position of the filter assembly). Since the instantaneous field of view is increased and the incoming radiation energy is conserved with respect to the imaging process, the amount of radiation incident on a pixel area is greater than it would be in the focal plane of the telescope.

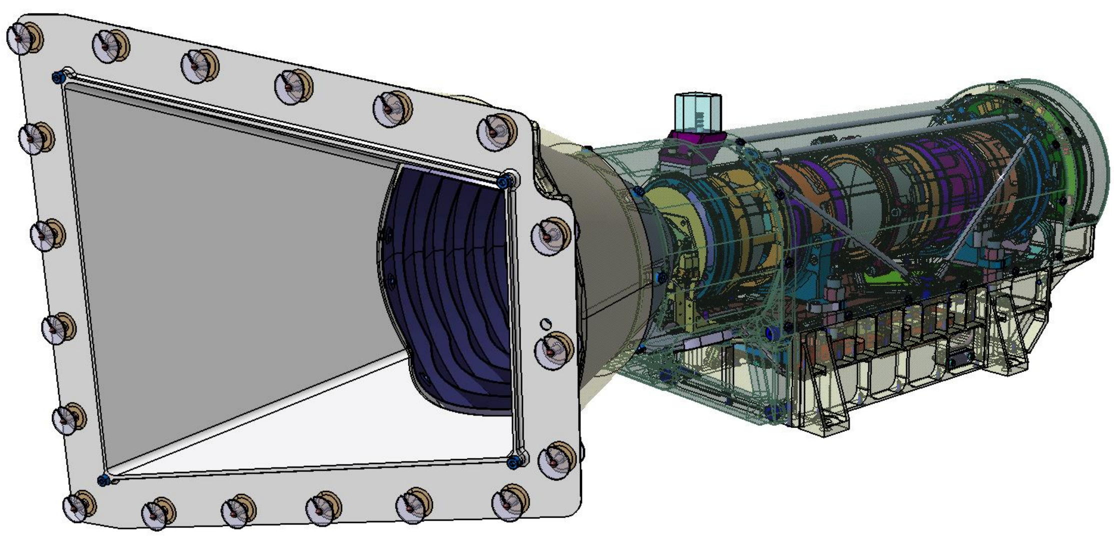

Figure 1. CAD model view of the VEM instrument design.

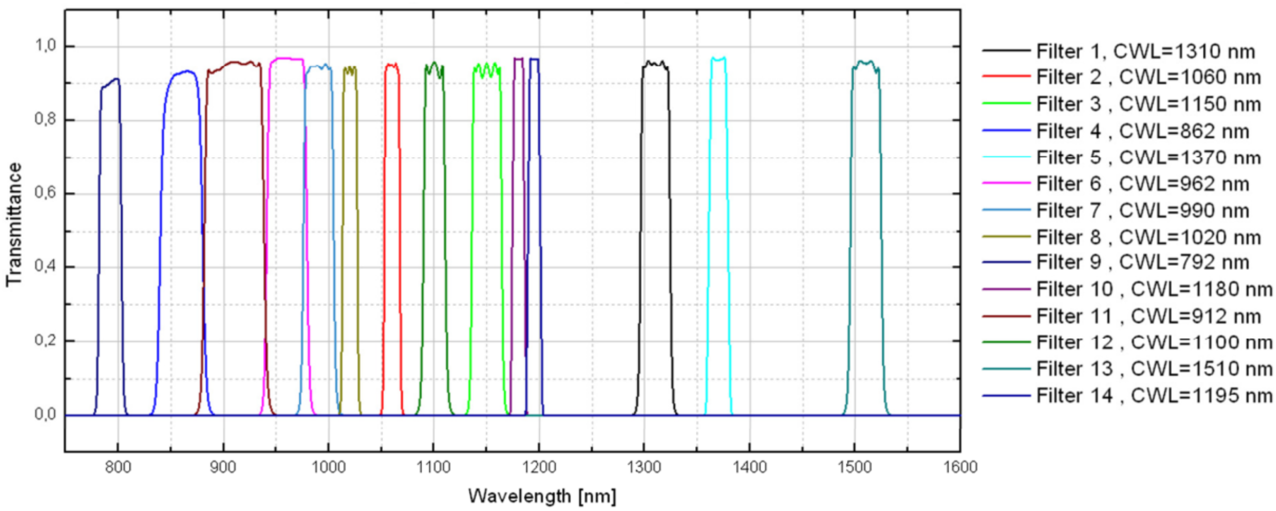

Figure 2. Transmission spectrum of the VEM optical filters as a function of wavelength. CWL: central wavelength. (*Credit*: CNES).

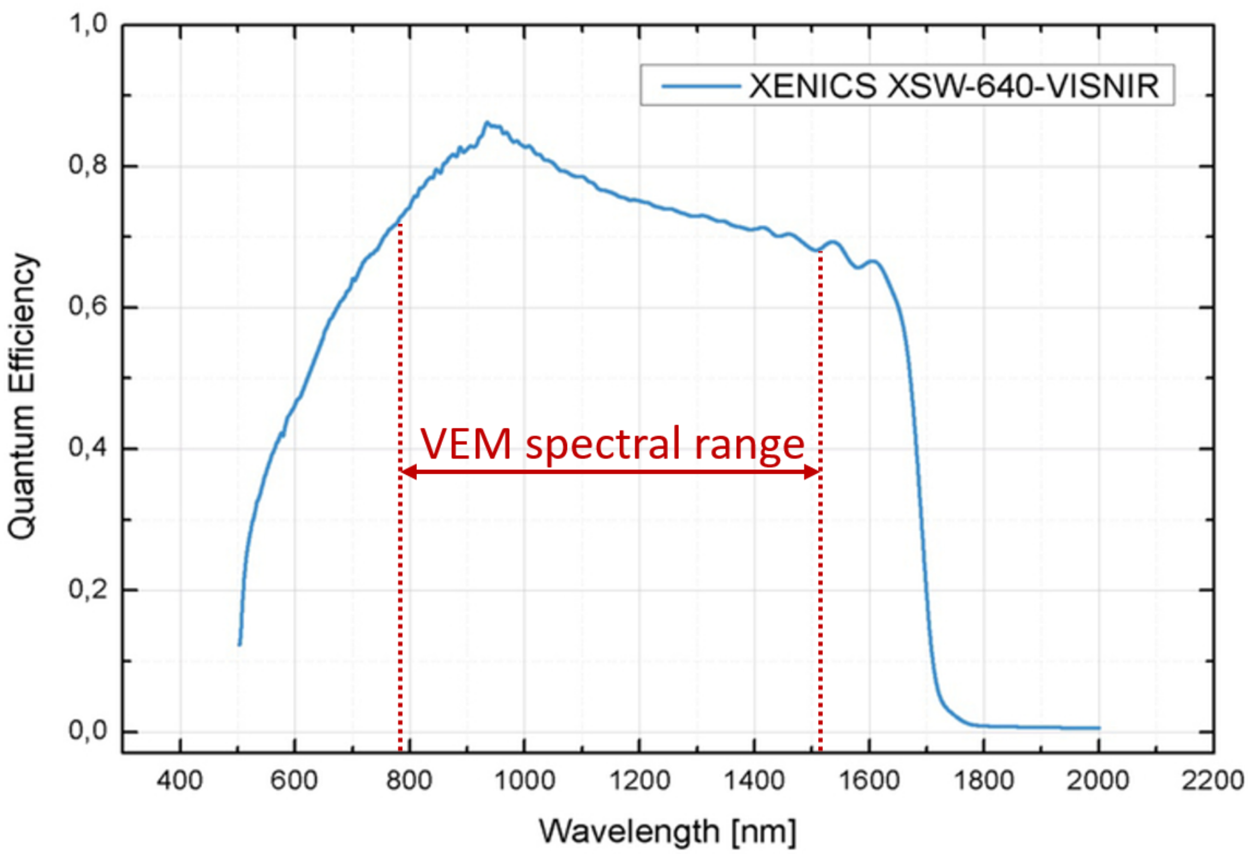

Figure 3. VEM detector (Xenics XSW-640) quantum efficiency as a function of wavelength. The red lines indicate the VEM instrument spectral range. The figure data has been taken and adapted from Refs. [8, 9]. (*Credit*: Xenics)

The total length of the optical system from the entrance telescope lens to the detector focal plane is approximately 300 mm and provides an instrument focal length of 16.4 mm. The across-track field of view of 46.4° corresponds to a swath width of 207 km at an orbit height of 250 km. This allows for thorough sampling of the Venus surface emissivity and a suitable orbit-to-orbit repeat coverage. A more detailed description of the VEMO design and its key optical parameters is provided in Refs. [6, 7].

With VEMO, each filter band is imaged onto an InGaAs detector (Xenics XSW-640) with integrated thermoelectric cooler (TEC). A picture of the detector quantum efficiency (QE) as a function of wavelength is presented in Figure 3 [8, 9]. While the QE almost perfectly matches the wavelength range of VEM, the integrated TEC cancels the need of any additional cryogenic cooling. On the other hand, the InGaAs type detector provides a rather high dark current along with its sensitivity to proton irradiation. However, this effect can be minimized by radiation spot shielding at detector level as has been already implemented in the VEM mechanical design and proven by radiation sector analysis. The detector array consists of 640 x 512 pixels with 20 µm pitch and is read-out via an analogue electronic board, which is connected to the instrument controller unit via PCB flex harness. In order to transfer the heat dissipated by the detector and TEC directly to the S/C rather than through VEM, a thermal strap including mechanical mounting interface is provided. The detector operating temperature is currently baselined at 0°C to reduce the dark current and enhance the instrument performance in terms of the signal-to-noise ratio (SNR) for the individual filter bands. Further cooling of the detector via the TEC is possible and only limited by VEM thermal design and the interface temperature at the second thermal reference point (TRP2) provided by the S/C.

An optically transmissive turn window unit (TWU) is mounted in front of the entrance optics in order to protect VEM against contamination and atomic oxygen during the aerobraking phase. The TWU mechanism design is depicted in Figure 4. It is a one-shot device based on a thermal knife principal. The TWU main structure consists of the turn window base that is mounted to the instrument and a movable turn window frame. The actuator mechanism consists of a spring, two bearings, two redundant resistors and a polymer wire. A torque on the window frame is induced by the spring, while the frame itself is held in its position by the wire. Therefore, the wire will be continuously in a tightened condition, while being wrapped around and in direct contact with the two resistors. By applying electrical power to one of the two resistors the wire melts and the mechanism rotates until it hits a stop in a position where the window is not longer in the optical path. The TWU is also equipped with two Hall sensors for monitoring the current state of the mechanism (open or closed). The magnetic field to activate the Hall sensors is provided by a small magnet present inside the turning frame. The frame itself is mounted to the base via the two bearings, which allows for the necessary rotational degree of freedom to open the TWU. Activation of the mechanism is done through the instruments power supply unit, which is electrically connected to the TWU.

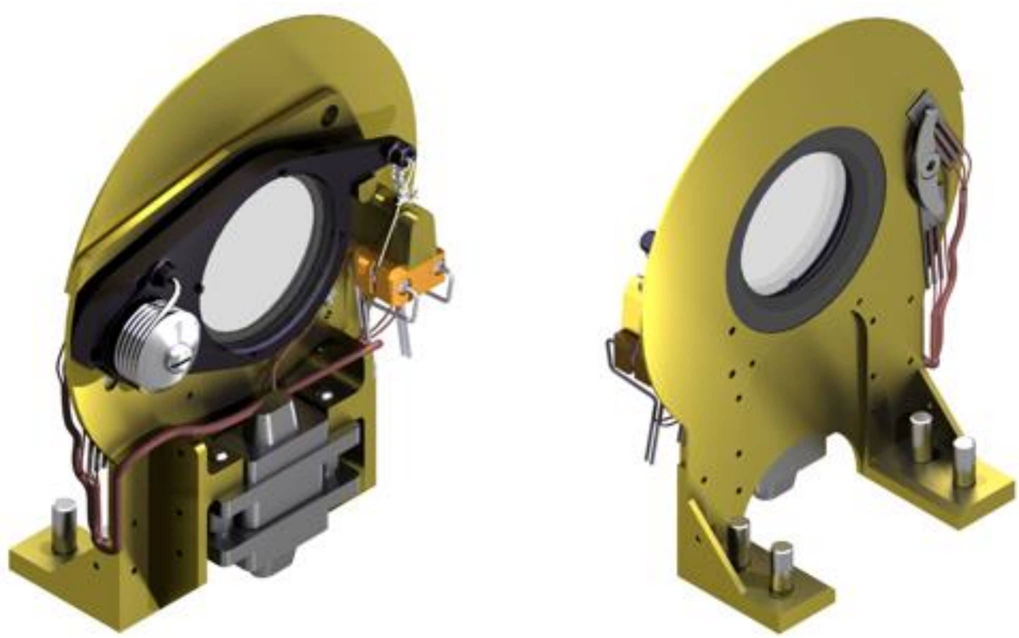

Figure 4. CAD model front (left) and rear (right) view of the VEM turn window unit.

The TWU window is made of fused silica with an AR coating optimized for the NIR region, in order to withstand all environmental effects during mission lifetime, including radiation and atomic oxygen, and to provide a high transmission of >98%. This allows for scientific observation even when the window is closed. It is currently planned to activate the mechanism and to open the window prior beginning of the nominal VEM science operation. However, if no significant degradation of the window is measurable at that time, the firing of the mechanism might become optional.

A two-stage baffle is mounted in front of the TWU. The inner baffle cone is a multi-vane structure with the key function to suppress potential straylight entering the VEM optical system. Since the instrument is tilted by an angle of 30° compared to the S/C panel for VERITAS a baffle shield is attached on top of the baffle cone. It provides another S/C mounting IF and shall prevent high temperatures on the baffle cone due to direct sun illumination.

The VEM instrument for VERITAS and the VenSpec-M instrument for EnVision are being developed almost simultaneously. This opens the path for a unique and efficient instrument development approach. Based on the system level, interface and environmental requirements of both missions, a single instrument design is to be established. Therefore, the identification of driving requirements is a key task to create an envelope for the instrument requirements defining the VEM/VenSpec-M design. As a result, the differences between VEM and VenSpec-M shall be very minor without affecting the instrument performance and quality. One example of a minor difference is the shape of the baffle shield (the baffle cone is identical), which is currently slightly different in VenSpec-M because of the accommodation onboard the EnVision S/C.

The VEM/VenSpec-M project is in its preliminary design phase. The preliminary design review (PDR) is currently planned in 2025 for VERITAS and EnVision. If a joint instrument design can be sustained at that time, despite the constraints of both missions, the following instrument qualification campaign can be made very effective. In this case, the worst-case environmental loads, e.g. for mechanical, thermal and EMC testing derived from the two missions will be applied. Two flight models (FMs) are currently scheduled for delivery to the VERITAS S/C in 2028 and one FM to the EnVision S/C in 2029. First VEM/VenSpec-M data obtained from Venus orbit is expected after launch of the two missions currently scheduled in 2031.

3. EXPECTED INSTRUMENT PERFORMANCE

The success of the VEM instrument development is mainly driven by the system performance. While the spatial resolution at Venus is limited to ~100 km because of scattering in the atmosphere, VEM needs to determine the relative surface emissivity with an accuracy of < 4% in order to match the scientific goals [10]. This is realized by providing a high performance in terms of the instruments SNR.

In order to estimate the SNR of VEM already in the preliminary design phase, an instrument performance model has been setup. The model evaluates the SNR, which is defined as the ratio of the signal level caused by the Venus night scene to the noise level created by the various noise contributors present in an optical instrument. On the detector side, it includes photon noise, dark current and read-out noise. The dark current increase because of proton irradiation includes also the strong dependence on the detector temperature. For the model, this dependence has been calculated based on detector proton test results, that have been performed at different detector temperatures up to the maximum total dose enveloping the VERITAS and EnVision radiation environment requirements. While the dark current increase because of proton irradiation can be easily an order of magnitude without any counter-measures (e.g. detector spot shielding as implemented in the VEM design), the read-out noise increase over the mission lifetime has been determined being negligible as of today.

For the VEM optics, the model includes the overall optical system transmittance including the TWU window, the lenses, the individual filters and the detector quantum efficiency (cf. Figure 3). Therefore, the SNR is calculated for each of the individual optical filter channels (cf. Figure 2). It also considers potential degradation of the transmittance because of contamination. To complete the model, it combines the instrument parameters with the Venus scenery based on spectral radiances from a theoretical model of the Venus atmosphere [8, 11]. To account for the push broom mode of VEM orbiting Venus permanently onboard the S/C, the orbit height and S/C velocity are further key parameters. SNRs are calculated for a ground sampling distance (GSD) of 10 km, which corresponds to the instruments sampling capability, which is an order of magnitude higher than the 100 km limit given by the Venus atmosphere. Oversampling of the moving Venus scene allows for the application of discrete TDI and macro-pixel binning techniques, which significantly

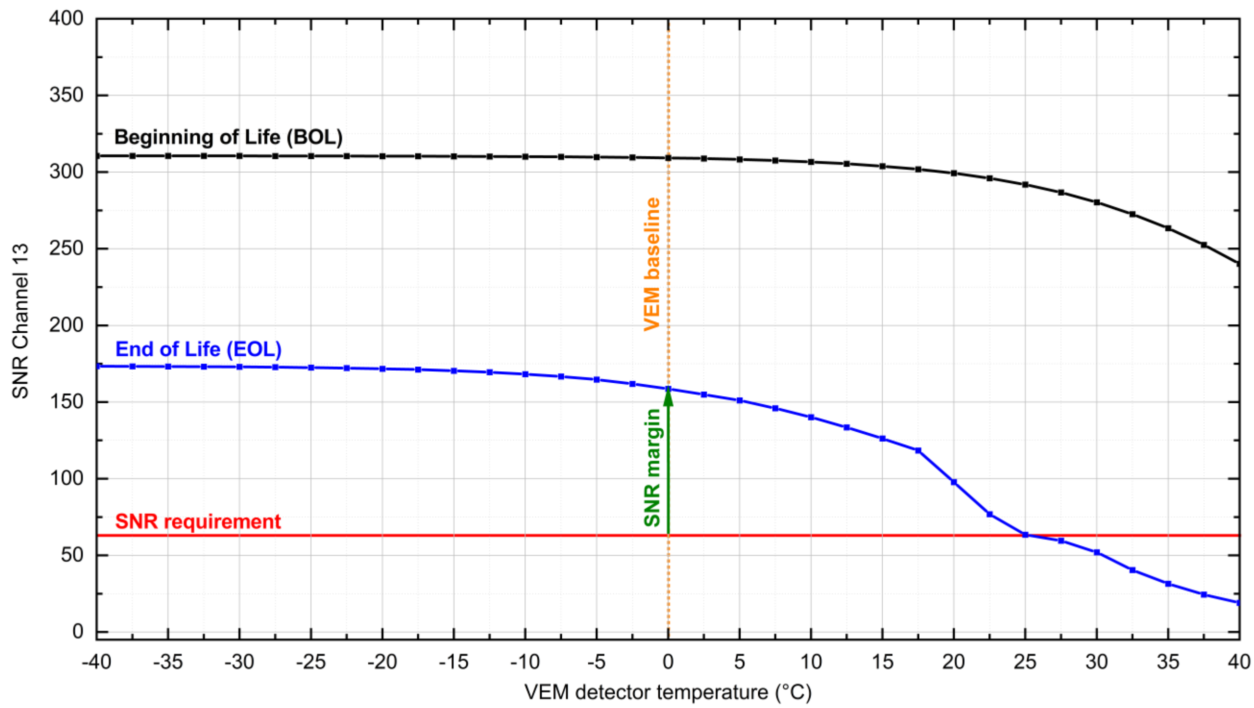

Figure 5. Expected VEM instrument performance in terms of the SNR as a function of the VEM detector temperature for filter channel 13 at mission beginning of life and end of life. The detector temperature is baselined at 0°C.

enhances the SNR. For slow orbits, temporal oversampling (TOS) can be used during one observation period of the Venus scene for exploiting the measurement time resulting in further enhancement of the SNR. This is done by acquiring several images in one scenery dwell time, as long as the gain in SNR by averaging the images exceeds the additional noise by the multiple read-out. TDI, macro-pixel binning and TOS are on-board pre-processing techniques planned for the VEM operations and are also included in the performance model. For a more detailed description of these techniques, refer to Ref. [8].

Figure 5 presents the SNR of VEM obtained through filter channel 13 as a function of the VEM detector temperature at mission beginning of life (BOL, black line in Fig. 5) and end of life (EOL, blue line in Fig. 5) for an orbit height of 250 km and a GSD of 10 km. These parameters have been chosen because they provide a worst-case view on the SNR. On the one hand the filter channel 13 is identified as the channel with the smallest SNR margin compared to its requirement. On the other hand, the low orbit height of 250 km limits the SNR because of the shorter integration available per observation period. The dashed orange line in Fig. 5 indicates the detector temperature of 0°C which is currently baselined for VEM operation. At BOL, the instruments SNR curve behaves almost flat up to detector temperatures of +10°C, where the read-out noise dominating. At temperatures above +10°C, the dark current becomes dominant. The SNR amounts to 309 for the detector temperature at 0°C, which is well above the requirement of 67 (cf. red line in Fig. 5). At EOL, the SNR has been remarkably reduced throughout the whole temperature range. This is mainly driven by the dark current increase because of proton irradiation over the mission lifetime. However, it is worth noting that all other noise contributors and degradation effects described earlier are also considered. The SNR amounts to 158 for the detector temperature at 0°C. Accordingly, the green arrow in Fig. 5 indicates a positive SNR margin of > 100%, which is still well above the SNR requirement. The SNR curve shows a noticeable kink at around +20°C. This is related to the VEM detector saturating already before the end of the observation period because of the dark current increase. Typically, TOS can be used in such a situation to improve the SNR. However, this is only possible if the remaining observation time for the current Venus scene is sufficient for another image acquisition. Here, the onset of TOS with a second image acquisition starts at temperatures above +25°C, visibly stabilizing the SNR.

The dark current increase by proton irradiation is significantly reduced in VEM, because of efficient detector spot shielding. However, it is important to note that the performance model does not yet include potential degradation due to straylight. Improvements in the VEM performance can be expected through further reduction of the dark current, e.g. by additional detector spot shielding, as well as enhanced active cooling with the TEC to detector temperatures below 0°C. Our ongoing investigations following the detector proton irradiation tests also indicate, that implementing regular detector annealing at moderate temperatures during cruise phase can have a positive impact on the dark current reduction and thus the SNR. The annealing effect has been controversly discussed in the literature [12−14].

4. CONCLUSIONS

We are developing a multispectral push broom imager for the two orbiter missions VERITAS led by NASA and EnVision led by ESA. By exploiting the spectral windows present in the near-infrared spectral region as demonstrated by the VIRTIS instrument on ESAs Venus Express mission, VEM will be the first flight instrument that allows for global mapping of the Venus surface emission with a coverage of >70% and will retrieve relative surface emissivity better than 4%. Our performance analysis results demonstrate, that the current VEM design provides a minimum SNR on the order of 100 with sufficient SNR margin > 100% at mission end of life, already considering possible degradation effects such as dark current increase due to proton irradiation on the InGaAs type VEM detector. The implementation of radiation spot shielding around the detector and operation at low temperatures have been identified as efficient counter-measures to maintain the VEM performance throughout the mission lifetime. At the moment, the VEM development is in its preliminary design phase with the PDR currently scheduled in 2025 for both missions. The delivery of the flight models to the S/C primes is planned in 2028 for VERITAS and 2029 for EnVision. First VEM/VenSpec-M data obtained from Venus orbit is expected after launch of the two missions currently scheduled in 2031. In combination with high spatial resolution data provided by radar mappers planned on both missions, VEM will open the path for revealing the geological evolution of Venus.

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