# Characterisation of the CCD Dark Current in the UVIS Spectrometer for the ExoMars Trace Gas Orbiter Mission

**Shaun Andrews[1,2]**

**Supervisors: Jon Mason[2], Manish Patel[2]**

[1]Department of Aerospace Engineering, University of Bristol [2]School of Planetary and Space Sciences, The Open University

## Abstract

The Ultraviolet and VIsible Spectrometer (UVIS), on-board the ExoMars Trace Gas Orbiter, was launched in 2016 and is designed to probe Ozone and Aerosols in the martian atmosphere. Its nadir channel performance is limited by the dark current generated from the temperature of the CCD. This research has produced a comprehensive analysis and characterisation of the dark current, as well as developing a robust method of dark current correction. Quadratic programming is used to generate artificial dark frames via optimal weighting of darks recorded in-flight. This method, combined with optimised binning, shows significant reduction in noise.

## Dark Current Removal using 2D Fourier Domain Filtering

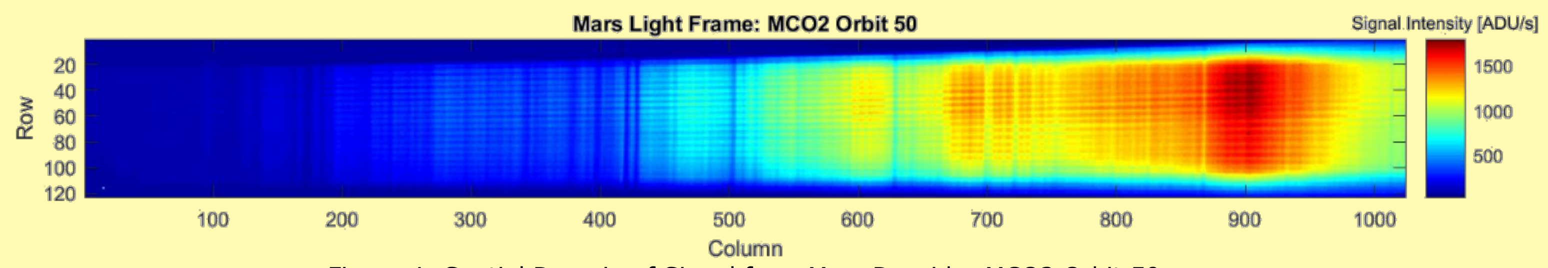


Figure 4: Spatial Domain of Signal from Mars Dayside: MCO2 Orbit 50

This method takes advantage of the fact that most of the power within a UVIS spectrum (Fig 4) resides at low frequencies. By applying a Fast-Fourier-Transform (1) to the frame, a two-dimensional frequency distribution can be obtained (Fig 5). The centre of this frame shows that low frequency components dominate, and the distinctive cross is representative of increasing harmonics that sum to form the bulk of wanted signal. All other components are extremely high harmonics that are present in order to produce the lowest order pixel per pixel variations. As the dark current is a background signal, commonly with an order of magnitude lower than the desired spectra, carefully removing selected high frequency components can suppress the dark current. Circular, rectangular

$$F(u,v) = \sum_{x=1}^{X-1}\sum_{y=1}^{Y-1} f(x,y)e^{-j2\pi(u\frac{x}{X}+v\frac{y}{Y})} \quad (1)$$

and cross shape low-pass filters were applied to Mars spectra, obtained in MCO2. Investigations were also made into using the Fourier filtering method to remove perodic electronic noise, as well as cosmic rays.

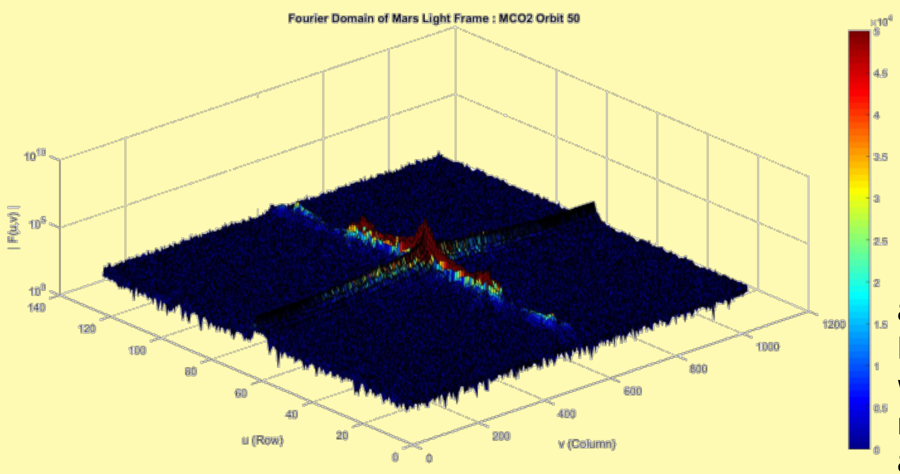


Figure 5: Fourier Domain of Signal from Mars Dayside: MCO2 Orbit 50

The first approaches using this method seem promising. Analysis into the spectra (Fig 6) of a filtered frame, processed using an 80% circular low pass filter, indicate a consistent signal reduction across the frame; to be expected with removal of the dark current level. However, removing the high frequency components has a smoothing effect, and the spectral resolution is seen to reduce, especially at short wavelengths.

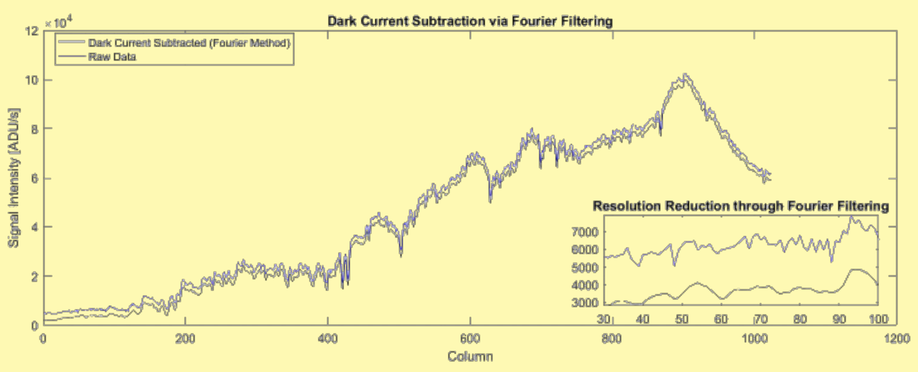


Figure 6: Mars Dayside Spectra before and after Fourier dark current subtraction

## Motivation and Background

**The ExoMars Trace Gas Orbiter (TGO), NOMAD and UVIS**

ExoMars TGO (Fig 1) is a joint mision between the European Space Agency and Roscosmos, with the aim of better understanding methane and other gases present in small concentrations within the martian atmosphere. NOMAD (Nadir and Occultation for MArs Discovery) is a suite of three spectrometers onboard TGO (Fig 2)- two infared and one ultraviolet. Its purpose is to perform high-sensitivity orbital identification and mapping of methane and many other species, via both solar occultation and direct reflected-light nadir observations [1].

UVIS is NOMAD's ultraviolet spectrometer (Fig 3), developed by The Open University and The Belgian Institute for Space Aeronomy. It will image the wavelength domain between 200 and 650 nm, covering and providing more information about several interesting molecules, such as ozone, $SO_2$ and aerosols. Light is collected in either the solar occultation or nadir telescope and fed to the spectrometer via optical fibres. The light is then directed through a diffraction grating, and the resultant spectrum read-out from a CCD detector via on-board electronics.

Figure 1: Artist's Impression of TGO

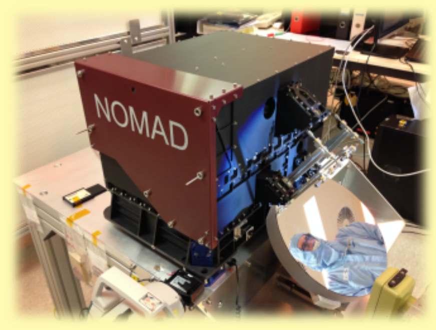


Figure 2: The NOMAD suite

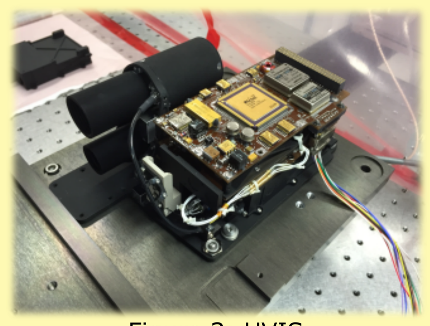

Figure 3: UVIS

**CCD Dark Current**

Dark current is generated from thermal energy within the silicon lattice of the CCD (Charge Coupled Device) array. Thermally generated electrons are created independently of photons striking the detector. These electrons are captured in the potential wells of the CCD, and measured as an additional component of signal. The dark current, and its associated noise, is purely unwanted signal, and must be removed before the spectrum of a frame can be analysed. Dark current exponentially increases with temperature, and this dependance varies both regionally across the CCD and at an individual pixel level.

The characterisation of the UVIS dark current was conducted after: 1) The CCD electronic bias noise was removed and 2) Bright pixels (Pixels with signal values significantly larger than the frame mean) have been suppressed. To measure the dark signal, dark frames (where the boresight is closed) and dark sky frames (where the boresight points at dark space) were used.

Dark and dark sky frames were recorded in ground calibration, as well as in-flight through all mission stages: NEC (Near Earth Commissioning), MCC (Mars Capture Cruise) and MCO1/2 (Mars Capture Orbit 1 and 2).

## Dark Current Mission Stability

As a thermal process, dark current can be modelled using the Arrhenius Law[2] (2). Analysis confirmed that, after bright pixel

$$D_{ADU_{x,y}} = D_{0ADU_{x,y}} T^3 e^{-\frac{E_a}{kT}} \quad (2)$$

removal, the majority of pixels complied to this model across all observations made (Fig 7). Although degradation in bright pixel count was observed over mission time, there is no such degradation in the dark current. This allows the use of a 'dark library', consisting of all calibration and mission-obtained dark frames, to be used for dark removal. Modelling each pixel(x,y) allows a dark frame to be generated for any given temperature, and used to subtract from the light frame. However, not all pixels conform, leading to false subtraction in some areas of the CCD. UVIS expected operating temperature is 273-283K, where 5-20 ADU/s of dark current is predicted per pixel.

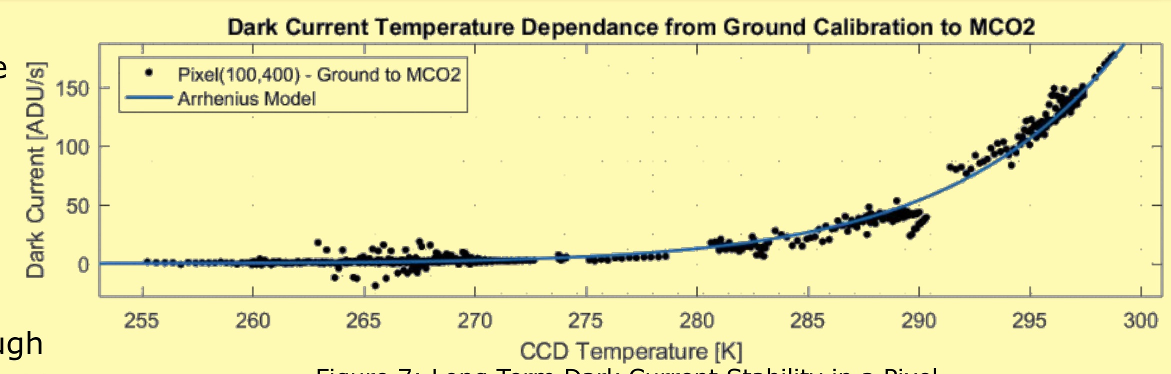


Figure 7: Long Term Dark Current Stability in a Pixel

## Optimisation of Artificial Dark Frames via Quadratic Programming

A reliable method of dark current subtraction is to use a master dark frame generated using the mean of multiple dark frames obtained under like conditions. As UVIS cannot control its temperature this is not possible. However, an artificial dark can be generated using a weighted sum of frames within the dark library; the weight is chosen based upon the similarity of the library dark to the true dark frame. As dark current is a small magnitude background component relative to the desired spectra, smoothness can be used as a measure for its presence within a frame. An algorithm (3) has been programmed that uses discrete derivatives between a pixel and its 8 neighbouring pixels as a smoothness indicator. Quadratic programming can then be implemented in order to optimise the weighting of dark library frames so as to generate a modelled dark frame (Fig 8) that best matches the conditions of the light observation, with the discrete derivative as the optimisation measure.

$$Min \rightarrow \frac{1}{2}x^TQx - c^Tx \quad (3)$$

$$s.t. \rightarrow x \succeq 0, 1^Tx = 1$$

$$Q = \sum_{r=2}^{122}\sum_{c=2}^{1023}\sum_{j=1}^{8}(D_{r,c} - D_{j_{r,c}})(D_{r,c} - D_{j_{r,c}})^T$$

$$c = \sum_{r=2}^{122}\sum_{c=2}^{1023}\sum_{j=1}^{8}(L_{r,c} - L_{j_{r,c}})(D_{r,c} - D_{j_{r,c}})$$


Figure 8: Dark Frame Modelled from Quadritic Optimisation


Figure 9: Original Measured Dark Frame

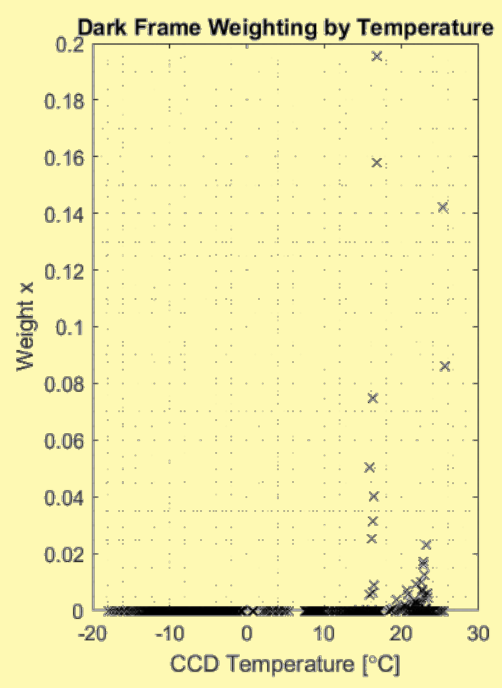


Figure 11: Weights Generated according to Dark Frame Temperature. Actual Temperature 19C

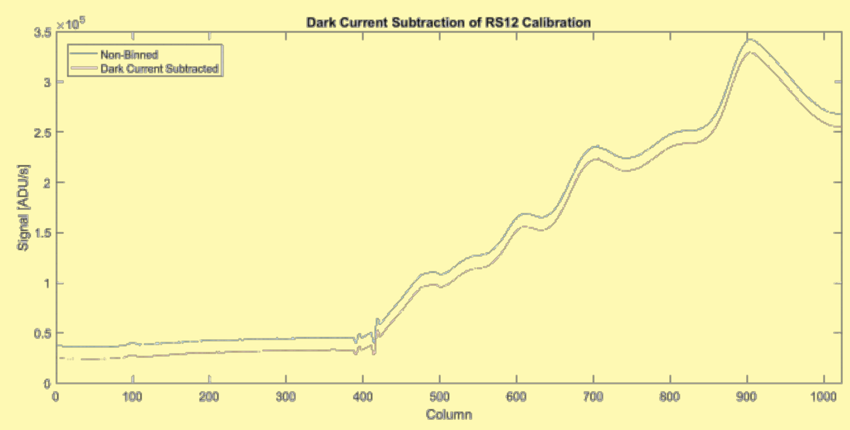


Figure 10: RS12 Dark Current Subtraction via Quadratically Optimised Dark

Whole frame mean residual dark current after application of the model is 1-10 ADU/s, with per pixel residual of <1 ADU/s. The weights are used as a measure of accuracy by back-calculating temperature (Fig 11); distribution about the recorded temperature implies a valid model dark frame. Unlike the fourier method, there is no compromise with resolution. However, there is no theoretical support to this method as it is effectively data mining for each dark frame.

## Regional Analysis for Minimisation of NESR

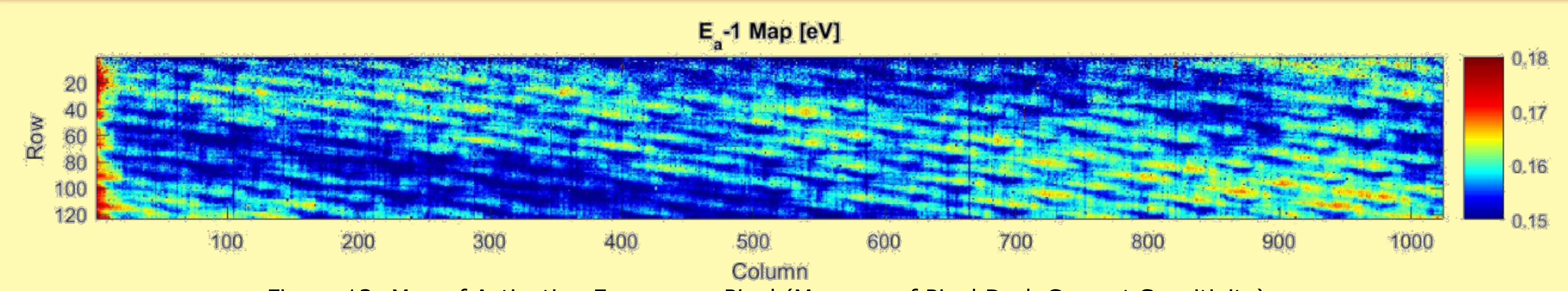


Figure 12: Map of Activation Energy per Pixel (Measure of Pixel Dark Current Sensitivity)

From the exponential fitting of each pixel, a map of pixel sensitivity to dark current can be generated (Fig 12), and used as a figure of merit for regional variation in dark current across the CCD. There exist two distinct bands across the CCD which respond more to temperature change than the surrounding frame, as well as a set of pixels on the left-hand side of the frame which respond far less. It can also be seen that entire columns exhibit greater responses, although this is likely a combination of dark current accumulation and readout effects. These variations of dark current are accounted for in subtraction methods. But despite this, the residual dark current within the cleaned frame will still vary according to the above pattern. It follows therefore that there exsists areas within the clean frame that contain less noise than others. These areas will give signal with better Noise Equivalent Spectral Radiance (NESR). An algorithm has been created that, given a wavelength band, scans through the frame and locates the best rectangular set of pixels to bin, such that the NESR is minimised. Figure 13 shows, that after dark current subtraction, the NESR is improved by an order of 10. After the optimal region has been located, the NESR is further reduced by an order of 1000 from the raw spectrum. Calculating the optimal region allows UVIS to reduce its data volume without compromising on its science objective. The optimal bin varies on the spectra, but all frames recorded thus far yield different rectangular bins between rows 40 and 100.

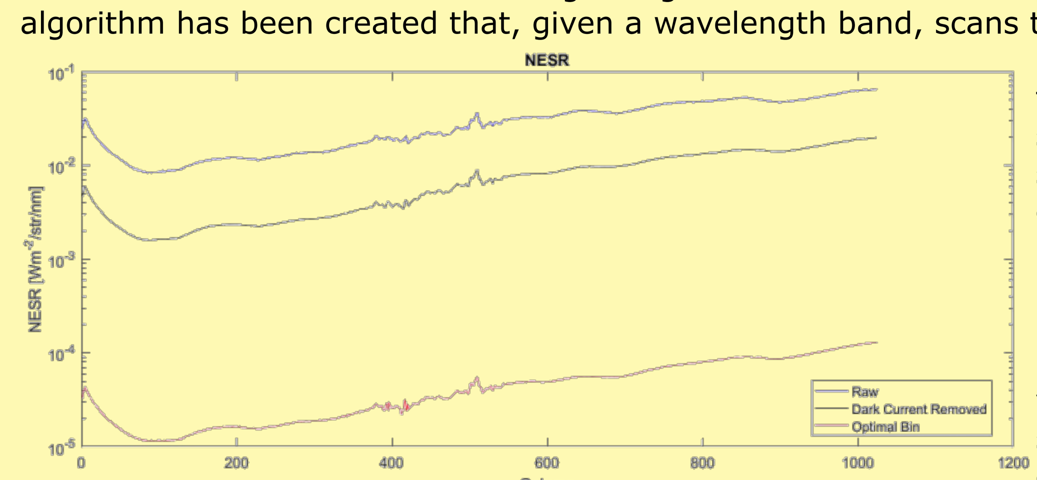


Figure 13: NESR Improvement

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