# WORLD SPACE OBSERVATORY - ULTRAVIOLET

# WSO-UV mission WUVS instrument FUV-UV CCD detectors qualification campaign main results

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World Space Observatory Ultraviolet (WSO-UV) is a major Russian-led international collaboration to develop a large Space-borne 1.7m Ritchey-Chrétien telescope and instrumentation to study the Universe at ultraviolet wavelengths. The WUVS spectrograph consists of three channels: two high resolution channels (R=50000) with a spectral range of 115-176 nm and 174-310 nm, and a low resolution (R=1000) channel with a spectral range of 115-305 nm.

The main challenges of the WUVS detectors are to achieve high quantum efficiency in the FUV-NUV range, to provide low readout noise (≤3 e$^-$ at 50 kHz) and low dark current (≤ 12 e$^-$/pixel/hour), to operate with integral exposures of up to 10 hours, and to provide good photometric accuracy. We present a summary of the measured and calculated key parameters of the WUVS detectors.

## WUVS CCD detectors description

WUVS (WSO-UV UltraViolet Spectrographs) spectrograph of the WSO-UV mission consists of three channels:

- VUVES: R=50000, 115-176 nm;
- UVES: R=50000, 174-310 nm;
- LSS: R=1000, 115-305 nm.

All three channels operate strictly in turn, each uses its own dedicated detector.
CCD enclosures and drive electronics are located inside an optical-mechanical unit of the spectrograph that is inside the instrumental compartment of T-170M telescope.
The companies, Teledyne e2v and RAL Space, designed and manufactured the WUVS detector subsystem which consists of three channels, each optimized for a specific range of wavelengths.
Each channel is made up of a 4k x 3k CCD272-64 image sensor in a custom vacuum cryostat (Enclosure) to maintain the detector's temperature at -100°C, an interconnection module, and a space-qualified Camera Electronics Box (CEB) linked by a cable harness (Fig. 1).
WUVS detectors should provide high sensitivity, high geometrical stability, high dynamic range, and low dark current. For cost-saving reasons the design of all three detectors should be identical, except for minor changes such as anti-reflection coating on the CCD and the selection of active output amplifiers.
To prevent contamination of the CCD, the enclosure should be sealed.
The Enclosure input window should be heated up to +22°C to prevent contamination of the window from the WUVS optical compartment.
The WUVS detectors are optimized to operate with low level signals at 173 K with a10-minute standard integration time.
The optical schemes of VUVES and UVES channels are optimized to use all available areas of the CCD detectors. The spectrum of the LSS channel is located along the bottom long side of the detector. This helps us to minimize the number of parallel transfers during the CCD readout.

## WUVS CCD current status

In 2019 4x CEB FM (Camera Electronics Box Flight Model) units were successfully delivered to Russia and passed incoming inspection (Fig. 7).
3x EQM Enclosures with 3 different CCDs (VUVES, UVES, LSS) were delivered to LPI and passed incoming inspection (Fig. 2).
In addition to the Teledyne e2v factory test, the quantum efficiency of LSS EQM Enclosure and CCD cooling system efficiency were measured in Russia.
FM Enclosures are expected to be delivered at the end of 2022.

## Quantum Efficiency measurements

The WUVS CCD272-64 is a semi-custom version of the device used for ESA's EUCLID mission.
It is a back thinned, back illuminated, 2-phase device pixel array organized by 4096 columns by 3112 rows. The pixel size is 12 µm square, but pixels can be combined in 2x2 groups to give an effective24 µm pixel size.
The two-phase split frame transfer architecture is used to provide maximum charge transfer efficiency after irradiation.
The CCD uses a low voltage process to minimise power consumption both on the device and in the drive electronics.
To provide the best readout noise characteristics, the conversion factor of output amplifiers isincreased and differential output architecture is used to enable common mode noise suppression.
The main challenge for WUVS CCDs is to provide optimised quantum efficiency over a very challenging spectral range from 120 nm to 320 nm. In order to achieve this, a novel process is used whereby the CCD has an anti-reflection coating over a part of the image area, that varies in thickness to match the required wavelengths. The coating is removed for the shortest wavelengths (111-170 nm), where the presence of the coating would degrade the quantum efficiency (see Fig. 4).
The assessment of quantum efficiency (QE) in the EUV and VUV ranges for modern CCDs is still limited due to the complexity of the necessary equipment, especially the source of monochromatic, well regulated, and uniform EUV and VUV radiations.
We measured the QE of the WUVS LSS detector. The LSS device has both anuncoated region (Fig. 5, lower part of the CCD) and a gradient AR coated region. The thickness of the AR coating is optimized for 180 nm on the left side of the CCD and for 310 nm on the right side (Fig. 5, upper part of the CCD), in accordance with the WUVS spectrograph dispersion.
We measured the QE in the111-320 nm range for the uncoated region. For the AR coated region, we chose 10 points of different thicknesses (see Fig. 6). The resultant measurements show a good compliance with the theoretical predictions made by Teledyne e2v.
QE was measured at Budker Institute of Nuclear Physics, Russian Academy of Sciences, Novosibirsk. The measurements were carried out at the beamline "Kosmos" using synchrotron radiation from the VEPP-4M storage ring. The beamline utilized a plane grating monochromator configuration. For suppression of the high energy radiation, a$MgF_2$ filter was used. The WUVS CCD Enclosure and the calibrated photodiode SPD (ФДУК-100УВ) were located on a remotely controlled movable optical bench inside the vacuum chamber, to be able to irradiate different areas of the devices and to switch the devices from CCD to SPD and back.
All the measurements were done at the working temperature of -100°C on the sensitive surface of the CCD.
We clearly see a great potential to improve the CCD responsivity in the UV using specially designed anti-reflection coating. For future FUV missions, a new special FUV anti-reflection coating should be designed.

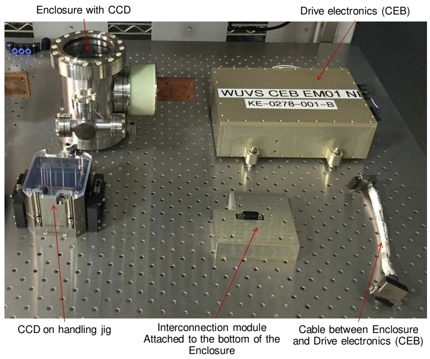


Fig. 1. WUVS detector Engineering model main parts (Teledyne UK, Chelmsford).

Fig. 2. EQM Enclosures at LPI climatic chamber before pump & bake procedure (Moscow, Russia).

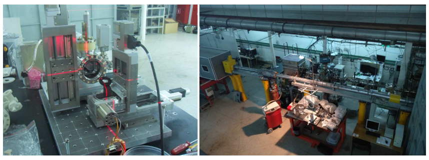

Fig. 3. EQM Enclosure at "Kosmos" metrological station (VEPP-4M synchrotron) during quantum efficiency measurements (INP, Novosibirsk, Russia).

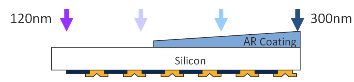


Fig. 4. WUVS CCD gradient antireflection coating.

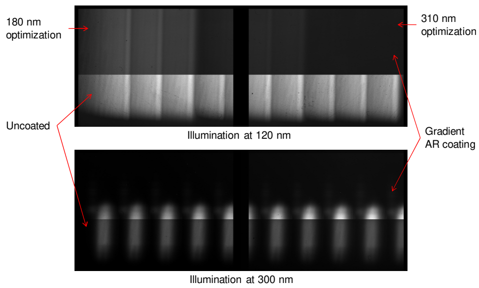


Fig. 5. EQM LSS CCD test images in FUV and NUV. The lower part of the CCD is uncoated, the upper part has gradient coating.

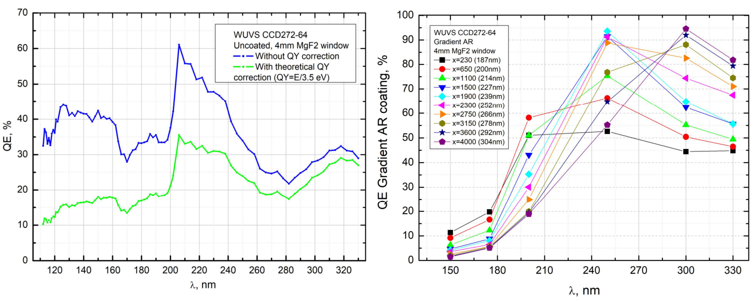


Fig. 6. EQM LSS Enclosure quantum efficiency measurement results (INP, Russia): uncoated region of the CCD (left), gradient AR coating region of the CCD (right).

Table 1. Main specifications of the WUVS detectors.

| Characteristics | VUVES | UVES | LSS |
|---|---|---|---|
| Spectral range, nm | 115-176 | 174-310 | 115-305 |
| CCD AR coating | Uncoated | Uncoated 174-200 Gradient 200-310 | Uncoated 174-200 Gradient 200-305 |
| Readout amplifiers | Top, Bottom | Top, Bottom | Left, Right |
| Size of photosensitive area, mm | 37.3 x 49.1 | | |
| Pixel format | 4096 x 3112 | | |
| Pixel size, µm | 12 | | |
| Readout speeds, kHz | 50, 100, 500 | | |
| Readout noise at 50/100 kHz, e$^-$ | 3/4 | | |
| Saturation signal, e$^-$ | 30000 | | |
| Digitalization, bits | 14 | | |
| Dark current, e$^-$/pixel/h<br>at the beginning of life<br>at the end of life | <br>3<br>9 | | |
| CCD temperature, °C | -100 | | |
| Enclosure foot temperature, °C | +20 | | |
| Thermal load at Cold finger, W | 3 | | |
| Typical exposure time, s | 600 | | |
| Data interface | SpaceWire 25 Mbits/s | | |
| Power, V | 27 | | |
| Power consumption, W | 10.5 | | |
| Mass, kg | 9.1 | | |

## CCD Drive electronics measurement

The Camera Electronics Box (CEB) was designed and built by RAL Space, STFC (UK). The CEB houses three camera electronics cards: a power supply card, a bridge card and a CCD camera card (see Fig. 7).
The CCD camera card provides the majority of the functionality within the CEB system, including the SpaceWire interface, video digitization, CCD bias voltage generation and CCD clock drivers.

Fig. 7. CEB Flight Model.

The CCD camera card contains two DCDS (Digital Correlated Double Sampling) video channels that provide the Correlated Double Sampling (CDS) and Analogue-to-Digital Conversion (ADC) which are required to sample and digitize the video signals from the CCD's two readout amplifiers. The ADCs run in parallel at 25 Mpixel/s and provide14-bit digitization.
The CCD camera card provides a variable pixel readout rate of 50 kHz, 100 kHz and 500 kHz, multiple windowed readout and on-chip pixel-summing modes.
The CEB communication interface with WUVS is SpaceWire and runs at 25 Mbit/s.
The RAL Space factory test ofFM CEB results is presented in Fig. 8.

| | | Port F | | | Port G | | |
|---|---|---|---|---|---|---|---|
| Readout Mode | Criteria | System Noise (ADU rms) | System Gain (e$^-$/ADU) | System Noise (e$^-$ rms) | System Noise (ADU rms) | System Gain (e$^-$/ADU) | System Noise (e$^-$ rms) |
| 50 kHz 1x1 Binning | < 3 e$^-$ rms | 0.790 | 3.299 | **2.61** | 0.810 | 3.184 | **2.58** |
| 50 kHz 2x2 Binning | < 3 e$^-$ rms | 0.849 | 3.202 | **2.72** | 0.877 | 3.173 | **2.78** |
| 100 kHz 1x1 Binning | < 4 e$^-$ rms | 0.922 | 3.290 | **3.03** | 0.946 | 3.211 | **3.04** |
| 100 kHz 2x2 Binning | < 4 e$^-$ rms | 1.001 | 3.221 | **3.22** | 1.029 | 3.143 | **3.23** |
| 500 kHz 1x1 Binning | < 40 e$^-$ rms | 2.020 | 3.294 | **6.65** | 2.081 | 3.215 | **6.69** |
| 500 kHz 2x2 Binning | < 40 e$^-$ rms | 2.663 | 3.203 | **8.53** | 3.058 | 3.150 | **9.63** |

| Parameter | Criteria | Channel 1 Transient | Channel 2 Transient |
|---|---|---|---|
| Crosstalk - Adjacent Pixels – High to Low Transient | < 3% | 0.034% | 0.033% |
| Crosstalk - Adjacent Pixels – Low to High Transient | < 3% | 0.044% | 0.008% |
| Crosstalk - Between Channels | < 100 ppm | -29.0 ppm | -12.8 ppm |

| Parameter | Criteria | Channel 1 | Channel 2 |
|---|---|---|---|
| Linearity | < 1% | +0.19%/-0.12% | +0.16%/-0.12% |

Fig. 8. CEB FM model test results with CCD (from up to down): system noise with CCD results, video channel crosstalk results, linearity results (50 kHz).

## CCD Enclosure cooling system verification

Teledyne e2v has designed and manufactured a custom cryostat (Enclosure) that can maintain the CCD at -100°C in ultra-high vacuum conditions over 9 years after delivery.
Inside the cryostat, only special low-gassing materials were used. Each Enclosure has a$MgF_2$window and the main body is made of austenitic stainless steel. The central duplex steel column holds the CCD sensor.
The thermal path for cooling the CCD to -100°C is managed by a high conductivity thermal connection to a heat-pipe on one of the inputs of the chamber. This has been modeled in detail to ensure that the total temperature difference between the input and the CCD is less than 5°C.
The WSO-UV spacecraft provides an isolated cold heat pipe connected with a large external radiator. This system maintains the temperature of the CCD Enclosure's "Cold finger" around -105°C.A Low-power heater was installed near the CCD for precise temperature stabilisation. The measured flatness of the CCD is less than 10 µm peak to valley.
To prolong the detectors' lifetime in orbit, we plan to heat up all the detectors for annealing every few months.
The results of the Enclosure cooling system verification confirm that the temperature difference between the CCD and the "Cold finger" is 5°C.

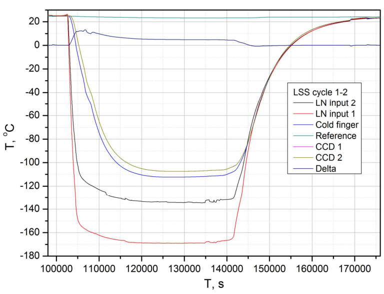


Fig. 9. EQM Enclosure cooling system verification (INP, Russia).