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WSO-UV mission UV CCD detectors Qualification campaign main results

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WUVS (WSO-UV UltraViolet Spectrographs) consist of two high-resolution spectrographs (R=50000) covering the Far-UV range 115-176 nm and the Near-UV range of 174-310 nm, and a long-slit spectrograph (R=1000) covering the wavelength 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) consist 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 enclosure and drive electronics are located inside an optical-mechanical unit of the spectrograph that is inside the instrumental compartment of T-170M telescope.

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 detector's temperature down to -100°C, an interconnection module and a set of space-qualified drive Camera Electronics Boxes (CEBs) linked by a cable harness (Fig. 1).

WUVS detectors should provide high sensitivity, high geometrical stability and high dynamic range, low dark current. For cost-saving reason the design of all three detectors should be identical, except minor changes like anti-reflection coating on the CCD and 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 on the window from the WUVS optical compartment.

The WUVS detectors were optimized to operate at low level signals at 173 K with 10 min standard integration time.

The optical schemes of VUVES and UVES channels are optimized to use all available area of CCD detectors. The spectrum of LSS channel is located along the bottom long site of the detector. It helps us 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 Enclosure with 3 different CCDs (VUVES, UVES, LSS) were delivered to LPI and passed incoming inspection (Fig. 2). In addition to Teledyne e2v factory test, the quantum efficiency of LSS EQM Enclosure and CCD cooling system efficiency were measured in Russia.

Quantum Efficiency measurements

The CCD272-64 to be used for WUVS was a semi-custom version of the device used for ESA's EUCLID mission.

It is a back thinned, back illuminated, 2-phase device with a 4096 column by 3112 row pixel array. The pixel size is 12 µm square, but pixels can be combined in 2x2 groups to give an effective 24 µm pixel.

To provide the best readout noise characteristics, the conversion factor of output amplifiers was increased and differential outputs were used to enable common mode noise suppression.

The main challenge for WUVS CCDs is to provide optimized 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 lowest 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 CCD is still limited due to the complexity of the necessary equipment, especially the source of monochromatic, well regulated and uniform EUV and VUV radiation.

We measured QE for the WUVS LSS channel. The LSS device has both uncoated region (Fig. 5, lower part of the CCD) and a gradient AR coating of varying thickness, which 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 WUVS spectrograph dispersion.

We measured QE in 111-320 nm range for the uncoated region and at 10 points of coated region of different thickness (see Fig. 6). The resultant measurements show a good compliance with the design and theoretical predictions made be 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 employed a plane grating monochromator configuration. For suppression of the high energy radiation, MgF_2 filter was used. WUVS CCD Enclosure and a 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 was done at 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 coatings. For future FUV mission, a new special FUV anti-reflection coating should be designed.

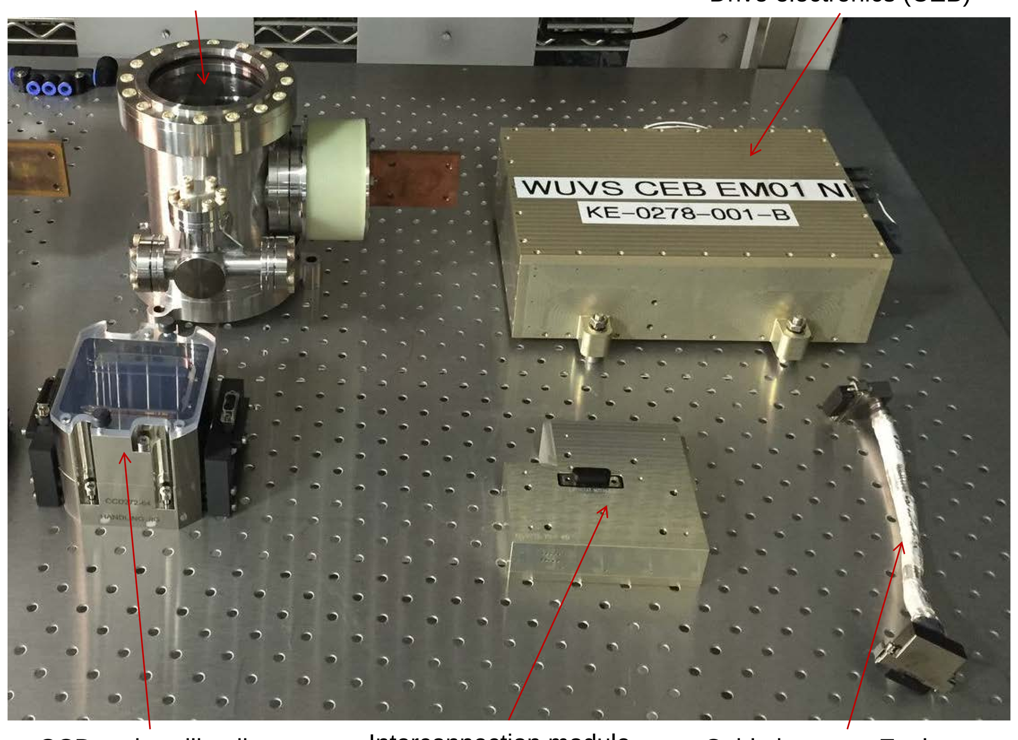

Fig. 1. WUVS detector Engineering model main parts (Teledyne UK, Chelmsford).

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

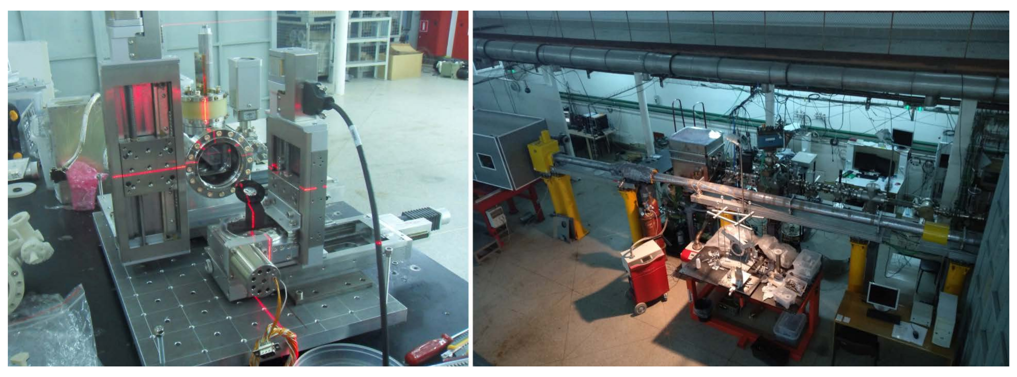

Fig. 3. EQM Enclosure at "Kosmos" metrological station (VEPP-4M synchrotron) during quantum efficiency measurements (INP, Novosibirsk, Russia).

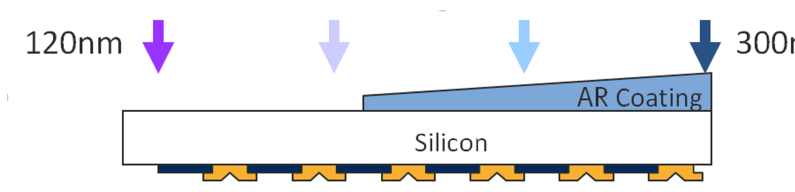

Fig. 4. WUVS CCD gradient antireflection coating.

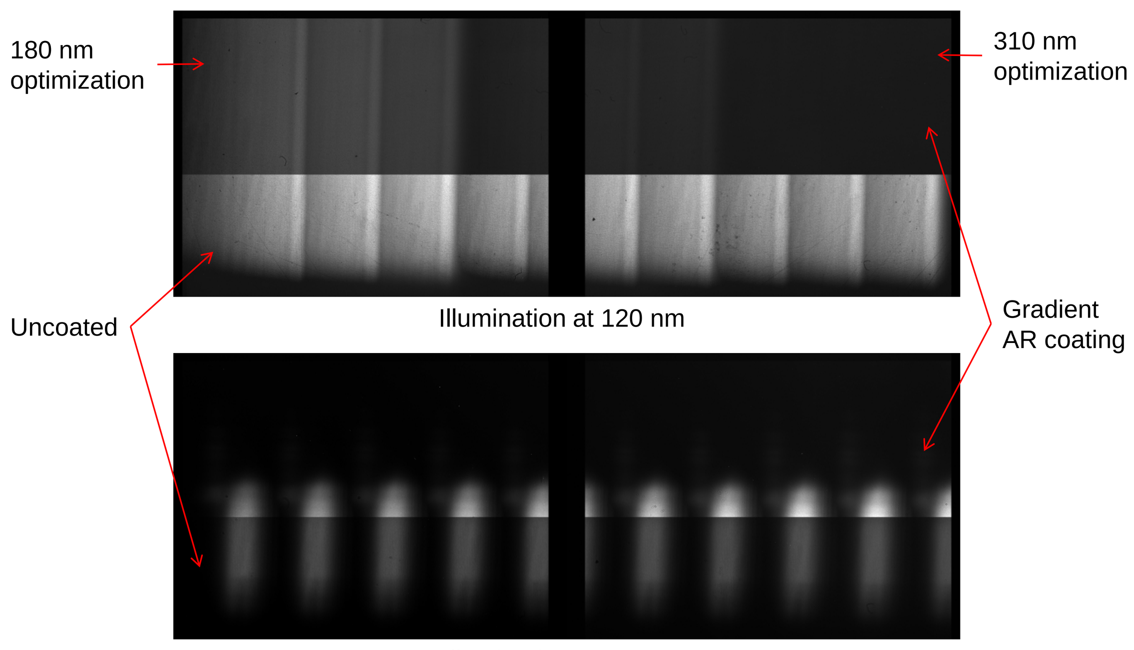

Fig. 5. EQM LSS CCD test images in FUV and NUV. The lower part of the CCD is uncoated, the upper part has gradient coating.

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 at the beginning of life at the end of life	 3 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: the 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) required to sample and digitize the video signals from the CCD's two readout amplifiers. The ADCs run in parallel at 25 Mpixels/s, and provide 14-bit digitization.

The CCD camera card provides variable pixel readout rate of 50 kHz, 100 kHz and 500 kHz, multiple windowed readout and on-chip pixel-summing modes.

The CEB communications interface with WUVS is SpaceWire running at 25 Mbits/s.

The RAL Space factory test of FM CEB results are 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

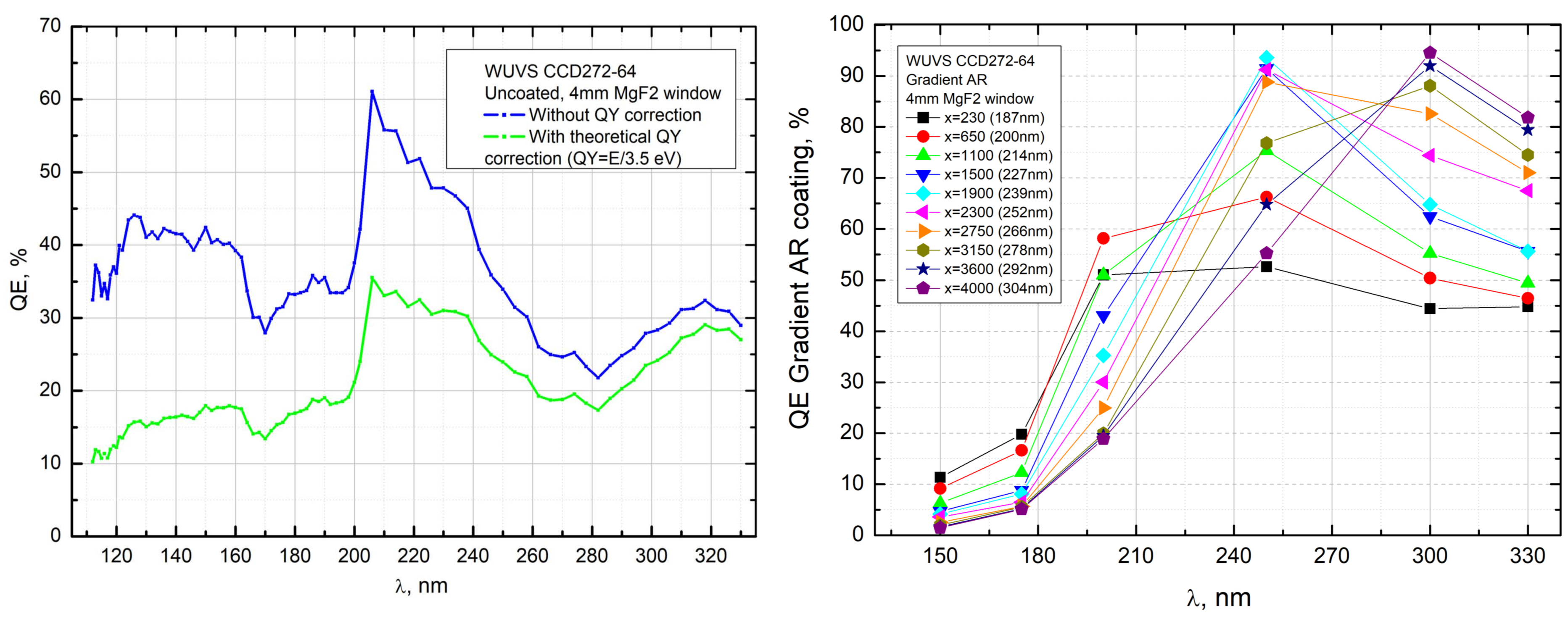

Fig. 6. EQM LSS Enclosure quantum efficiency measurement results (INP, Russia): uncoated region of the CCD (left), gradient AR coating (right).

Teledyne e2v has designed and manufactured 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 MgF_2 window, while the main body is made of austenitic stainless steel. The central duplex steel column is holding 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.

WSO-UV spacecraft provides an isolated "cold" heat pipe connected with a large external radiator. This system provides the temperature at the CCD Enclosure "Cold finger" about -105°C.

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 confirms that the temperature difference between the CCD and the "Cold finger" is 5°C.

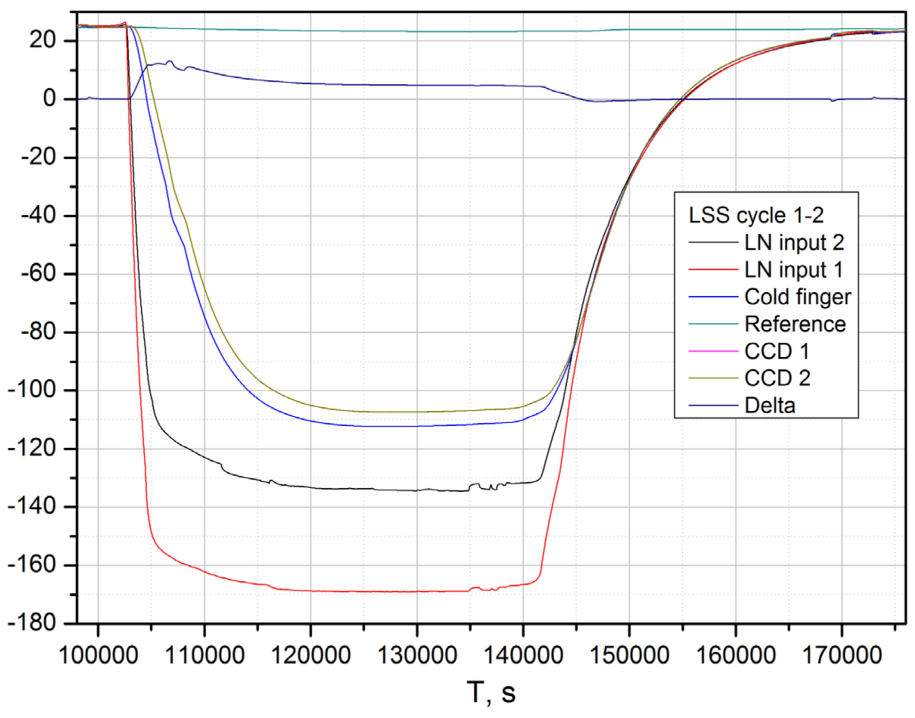

Fig. 9. EQM Enclosure cooling system verification (INP, Russia).