Design and characterization of the sCMOS detector for the comet interceptor camera

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Abstract

Comet Interceptor will travel to an little-processed long-period undiscovered comet, making a flyby of the chosen target when it is on the approach to Earth's orbit. The paper presents the architecture and performance of the backside illuminated sCMOS detector architecture and the corresponding detector control and front-end electronics as part of the COmet CAmera called CoCa[1].
The paper presents details of the selected back-illuminated low readout noise CIS115 detector from e2v/Teledyne, the design, implementation and test of the space qualified radiation tolerant readout electronics. The radiation tolerant detector in combination with the space qualified front end electronics resulted in an excellent readout noise performance of less than 4e$^-$. The paper shows electro-optical test results based on EMVA standard. Radiation test results done by our colleagues at the Open University provide minor performance degradation of the detector at the predicted mission radiation environment.
A novel readout scheme provides in rolling shutter operation exposure times less than the frame time. Electro-optical test results over the operation temperature range are part of the presentation. The paper discusses also interesting effects which were observed during detector characterization. An extensive investigation of the performance and redesign of the detector control (clocking and biasing) did provide major improvements.

Keywords: Comet Interceptor, sCMOS, electronics, detector, readout noise, rolling shutter, space, radiation

1. INTRODUCTION

The Comet Interceptor mission was proposed to the European Space Agency in 2018, and formally adopted by the agency in June 2022, for launch in 2029 together with the Ariel mission. Comet Interceptor will take advantage of the opportunity presented by ESA's F-Class call for fast, flexible, low-cost missions to which it was proposed. The call required a launch to a halo orbit around the Sun-Earth L2 point. The mission can take advantage of this placement to wait for the discovery of a suitable comet reachable with its minimum ΔV capability of 600 ms^{-1}. Comet Interceptor will be unique in encountering and studying, at a nominal closest approach distance of 1000 km, a comet that represents a near-pristine sample of material from the formation of the Solar System. It will also add a capability that no previous cometary mission has had, which is to deploy two sub-probes – B1, provided by the Japanese space agency, JAXA, and B2 – that will follow different trajectories through the coma. While the main probe passes at a nominal 1000 km distance, probes B1 and B2 will follow different chords through the coma at distances of 850 km and 400 km, respectively[1]. CoCa is the imaging system on Spacecraft A and is provided by a consortium led by the University of Bern in Switzerland including DLR Adlershof, LAM Marseille, the Konkoly Thege Miklos Astronomical Institute Budapest and their industrial partners. It is designed to provide high resolution imaging of the nucleus of the selected comet in 4 filters at selected broadband optical wavelengths. To provide high performance at low cost, it relies on designs successfully developed for previous flight programs. For a 1000 km fly-by, CoCa will provide 8 m per pixel images at a repetition frequency of 1 image per second. CoCa will therefore provide the highest quality imaging of the surface and the dust in the near-nucleus environment over a range of phase angles. The system is constructed to provide over 2500 images during the fly-by for subsequent downlink and can allow saturation on the nucleus to provide optimum signal-to-noise on the dust coma at all times through the fly-by. The optics of CoCa are protected from high velocity dust impacts by the Rotating Mirror Assembly (RMA) that will be provided by CSL in Liege and Thales-Alenia Space Switzerland.

2. THE COMET CAMERA INSTRUMENT

The camera consists of 3 units: The Proximity Electronics Unit (PEU) performs the analog signal conditioning and driving the detector. It is mounted separately from the Camera Support Unit (CSU) on the S/C. The unit however is needed to be in close range to the detector for EMC mitigation and high signal integrity. The Electronics Unit (ELU) drives the various elements of the instrument. The filter wheel and thermal control will be operated by a dedicated control board (FTC). The digital communications within the instrument and to the spacecraft will be performed by the digital processing module (DPM). The power conditioning for the instrument is performed by the power converter module (PCM). All 3 items of the CoCa instrument are illustrated in figure 1.

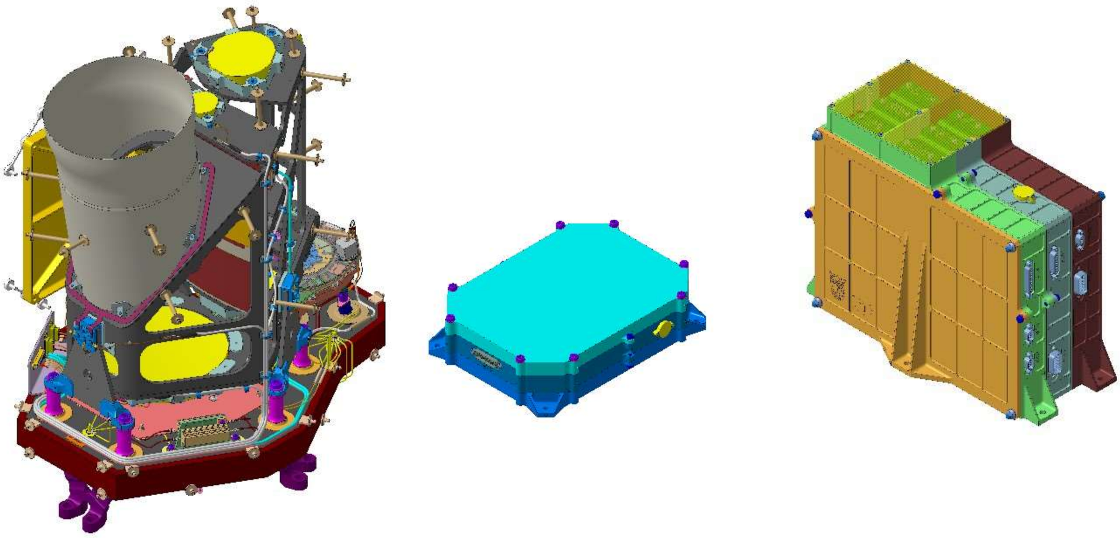

Figure 1. Hardware components of the CoCa instrument from left to right: CSU, PEU, ELU.

The optical system consists of a four mirror off-axis telescope with a nominal aperture of 135 mm, a focal length of 880 mm and a focal-ratio of f/6.5. The collected light from the target object passes through one of four optical filters on a four-position filter wheel before reaching the detector (Figure 2) in the focal plane assembly (FPA). The filters cover the wavelength range of 400-1050 nm with a nominal bandwidth of 100 to 150 nm.

The detector is a backside illuminated CMOS device from Teledyne e2v, based on the system currently in operation on the JANUS instrument on the ESA JUICE mission. A cold finger with a subsequent emitter will be used to reduce the detector operational temperature and with it, the dark current.

The CSU, being an optical device with strict stability requirements, must be thermally and mechanically decoupled from the S/C. In fact, thermo-elastic stresses and parasitic heat fluxes generated by the S/C must be minimized. For this reason, the whole unit is suspended on three titanium bipods and is completely wrapped in MLI.

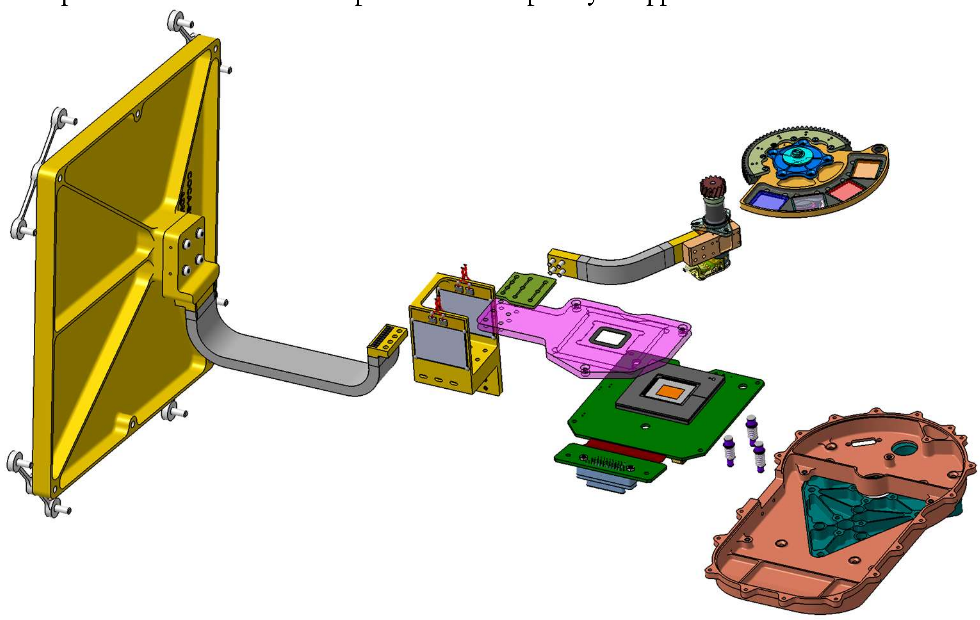

Figure 2. Assembly of the focal plane array assembly: FPA PCB (green), thermal hardware (yellow and violet) and housing (red)

3. THE CMOS CIS115 DETECTOR ARCHITECTURE

The CIS115 is a back-illuminated monolithic silicon CMOS detector with 2000x1504 pixels format. The pixel pitch amounts to 7µm. The 4T pixel design allows rolling shutter operation only[2]. The active area consists of 4 section, each 2000 by 376 pixels. The 4 analogue outputs drive the reference signal and video signal separately following the correlated double sampling technique[2].

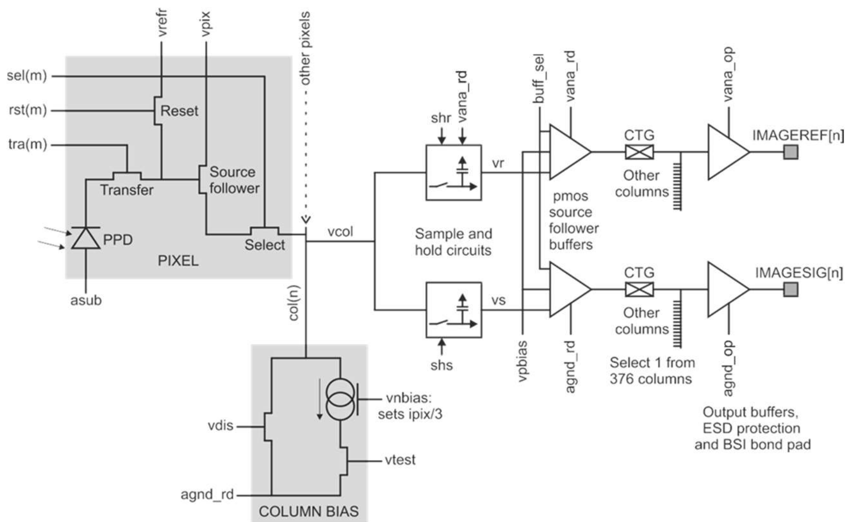

Figure 3. Pixel architecture and readout path

4. THE DETECTOR ELECTRONIS

The multiple outputs architecture requires the implementation of four signal chains to process the different video signals. For signal conditioning a subtractor calculates the difference between reference and signal level. To drive the differential inputs of the 14 bit ADCs the following full differential amplifier transforms the single ended unipolar signal into a full differential balanced output signal[3]. The noise optimized bandwidth of the signal chain provides a 3dB bandwidth of 70 MHz. For estimation of bandwidth we use the relationship between rise time and bandwidth according formula (1).

$$BW[Hz] = \frac{0.35}{rise\ time\ [ns]} \tag{1}$$

Figure 4 shows the CoCa electronics architecture based on radiation tolerant IEEE parts. The overall synchronization between detector signal timing and analogue to digital signal processing is implemented in radiation tolerant FPGA.

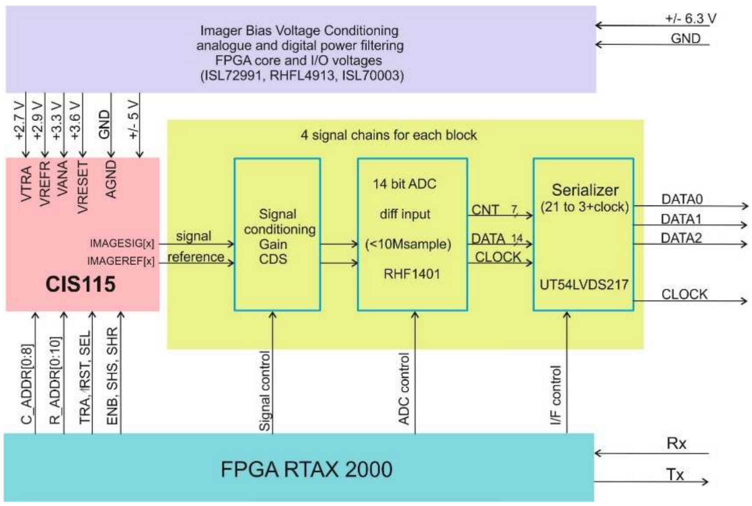

Figure 4. Radiation tolerant hardware architecture of the CaCa detector electronics

The radiation tolerant detector in combination with the space qualified front end electronics resulted in an excellent readout noise performance of less than 3e$^-$ (Figure 5). Radiation tests done by our colleagues at the Open University show only a minor performance degradation of the detector at the predicted mission radiation environment. A novel readout scheme provides in rolling shutter operation exposure times less than the frame time. The row addressing at the beginning of each line is split into two address decoders. The first address provides only a reset operation of the pinned photo diodes in line N+M. The second address M initiate the complete pixel operation to readout the signals. The number M presents the number of lines of integration time. Our test results using an autonomous electro-optical test system from the company Aspect Systems in Dresden did show excellent performance in VIS/NIR spectral range of the detector. The test results are based on the European Machine Vision Association standard EMVA Standard 1288. Data processing following the EMVA standard provides a wide knowledge of the electro-optical performance of the DuT. A high-speed data interface converts 21 bits data into three LVDS data streams. A phase-locked transmit clock is transmitted in parallel with the data streams over a fourth LVDS link. Every cycle of the transmit clock 21 bits of input data are sampled and transmitted. At a transmission clock frequency of 75MHz, 21 bits of TTL data are transmitted at a rate of 525 Mbps per LVDS data channel. Using a 75MHz clock, the data throughput is 1.575 Gbit/s (197Mbytes/sec). The complete FPA and readout electronics based on parts selection up to 300kRad TID immunity.

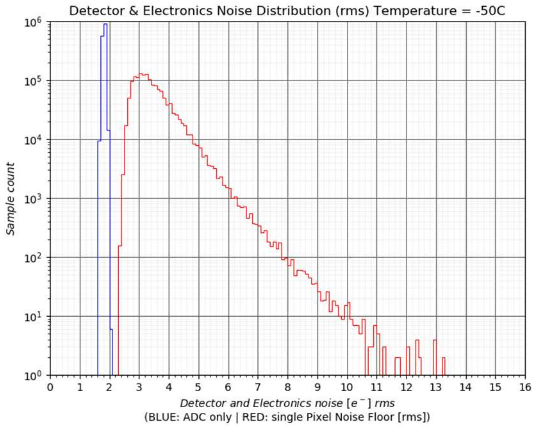

Figure 5. Test results of investigation of electronics noise (blue) and CIS115 noise floor (red) in darkness

5. DETECTOR CHARACTERIZATION LAB AND TEST RESULTS

While components and entire test benches are commercially available for many standard applications, comprehensive testing according to the EMVA Standard 1288 for the characterization of image sensors and cameras requires a flexible setup that needs to be capable of switching between a monochromatic light source for determining responsivity, temporal noise, linearity, non-uniformity, and pixel defects, a spectral light source for determining responsivity as a function of wavelength, and no light source for determining dark currents. Furthermore, controlling the temperature of the device under test is necessary to determine the temperature dependence of the dark current. In addition, testing devices over the entire spectral range spanning the visible (400 nm) to the long wavelength infrared (14000 nm) requires switching between different light sources and considerations such as the desired degree of automatization play a role when designing custom test bench setups.

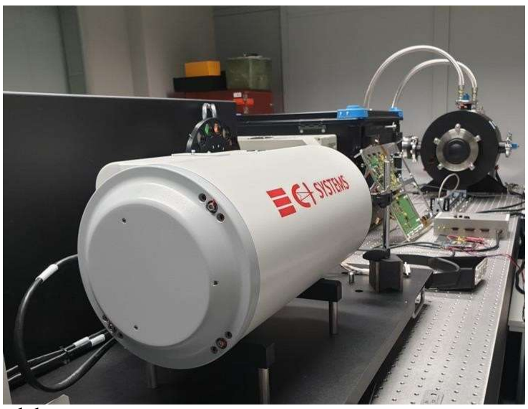

Figure6. Detector characterization laboratory.

Table 1. CIS115 electro-optical test results.

Parameter	**Results**	**Units**	Remarks
System gain[4]	~ 2	e^-/DN	±10 %
Total readout noise	3.5	e^- (rms)	90% of pixels, T= -50°C
Dark current rate	< 0.25	e^-/s	T= -20°C
Dark current (halve or double)	6.4	K	Average
Linearity	< ±2	%	
Full well	28	Ke^-	
QE	90.5	%	635 nm, FWHM: 18 nm, RT

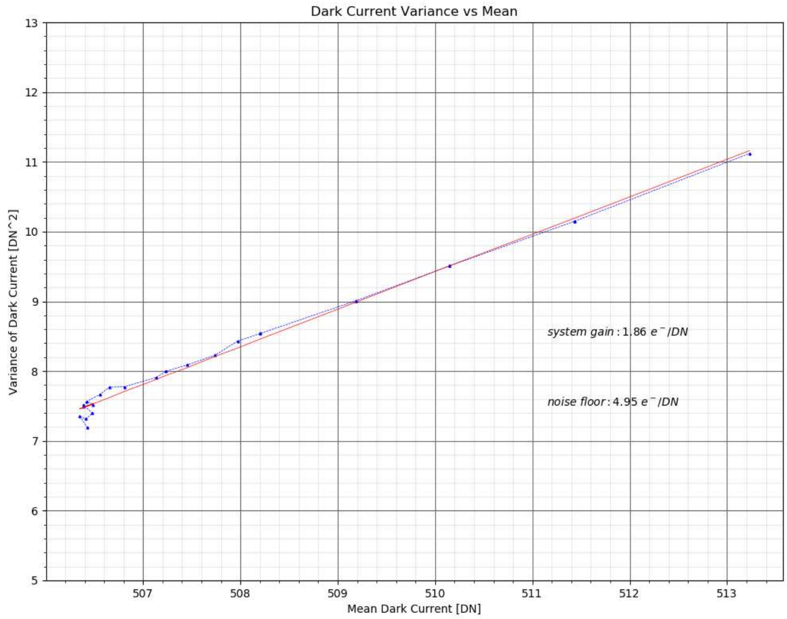

Figure7. Photon transfer curve[4] @ T= 0°C.

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