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Curved sensors: Experimental performance of CMOS prototypes and wide field related imagers

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ABSTRACT

The emergence of curved sensors technologies opens a new way to design compact high-performance optical systems. Recent progress on the French activity on curved sensors are presented in terms of optical performance and experimental results. The existing prototypes are demonstrated at TRL4, for VIS and SWIR domains. We present the roadmap jointly developed by CEA and CNRS to reach a higher TRL either on the performance of the devices or on the mass production processes. We present the results obtained on two demonstrators

Keywords: Curved sensors, wide field imagers

1. INTRODUCTION

The emergence of curved sensors technologies opens a new way to design compact high-performance optical systems. Today developed for civil or defense and security applications, several prototypes have been presented in recent years by industrials and academics, namely Sony, Microsoft , Teledyne-E2V, Stanford, ESO, NASA/JPL and CEA-LETI.

Recent progress on the French activity on curved sensors are presented in terms of optical performance and experimental results. At the device level, measurements obtained on full-frame visible sensors developed by CEA-LETI show an equivalent performance in terms of dark current, dark noise. At the system level, two wide field imagers have been designed and prototyped, and then used to characterize the overall performance of the curved-sensors-based systems: 1/ a fish-eye 180degrees FoV objective with a CMOS convex sensor, showing exquisite performance, much higher in terms of sharpness, chromatism and vignetting, and 2/ an ultra-compact 40 degrees FoV camera with an E2V concave sensor, which commercial version is currently embarked on drones and is six times bigger than the new one, for equivalent performance.

The existing prototypes are demonstrated at TRL4, for VIS and SWIR domains. We present the roadmap jointly developed by CEA and CNRS to reach a higher TRL either on the performance of the devices or on the mass production processes. Civil and defense markets are targeted, and the space domain must will take advantage of these new devices for the next generation of orbiting and embarked imagers.

2. DEVICES DEVELOPMENT AND CHARACTERISATION

CEA-LETI in collaboration with CNRS-LAM is in a phase of prototyping several curved detectors concepts. Such detectors have already shown promising results and demonstrated some of the improvements achievable in term of compactness and performances of the related optical designs. The off-the-shelf initial flat sensor consists of a silicon die glued on a ceramic package. Wire bonding from the die to the package surface provides the electrical connections.

Finally, a glass window protects the sensor surface from mechanical or environment solicitations. The curving process of these sensors consists of two steps: firstly, the sensors are thinned down with a grinding equipment to increase their mechanical flexibility, then they are glued onto a curved substrate. The required shape of the CMOS is, hence, due to the shape of the substrate. The sensors are then wire bonded keeping the packaging identical to the original one before curving. The final product is, therefore, a "plug-and-play" commercial component ready to be used or tested. Figure 1 shows the recently developed full frame CMOS visible sensors, fully functional.

Figure 1: Convex and Concave curved VIS CMOS (28mmx32mm, 20 Megapixels, curved down to a radius of 150mm), fully functional. The exquisite performance of the curved sensors is described in Chambion et al, SPIE Photonics West 2018.

A set of characterization measurements is performed on the curved concave detector and on its equivalent flat version and their results are compared. Typical measured quantities are: detector gain, dark current, readout noise, fixed pattern noise, dynamic range and full well capacity.

The following measurements were performed:

- ✓ For each exposure time, 30 frames were acquired.
- ✓ Firstly, exposures to uniform light -- also called flat fields -- have been performed, and then exposures in complete darkness.
- ✓ The exposure time has been changed with values ranging from 0.0002s to saturation, for flat field exposures, and to 0.96s for the dark exposures.
- ✓ The concave RC150 mm and a flat CMOS have been tested using the same set of measurements.
- ✓ The measurements were performed with camera gain set to 1.

We obtained the results in Figure 2. The linear increase of measured signal for exposure times larger than 0.048s is due to the accumulation of charges caused by the dark current. By fitting these data, we estimated the dark current in DN/s (the slope of the fit) and the bias level (the intercept of the fit). We obtained for the dark current a value of 80.68+/-0.7 DN/s for the concave sample (at 35.1°C) and of 94.90+/-0.59 DN/s for the flat sensor (at 34.9°C). The errors here are the 1σ errors on the linear fit.

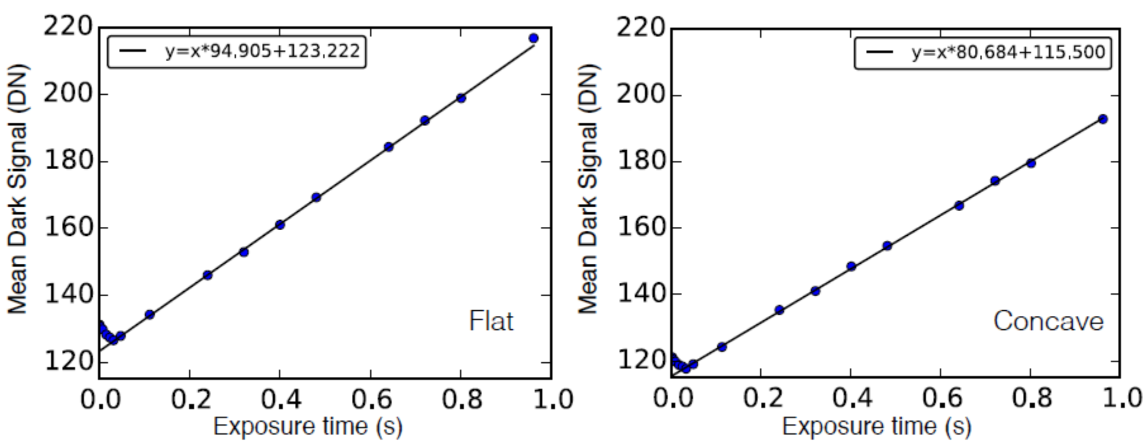

Figure 2 Mean dark exposure signal as function of exposure time. The black line is the fit to the data for exposure time larger than 0.048s. Left: data for the flat sensor. Right: data for the concave sensor

For the shorter exposure times, the counts on the sensor increase and the response is not linear. As this feature is present in both sensors, we concluded that it is an intrinsic characteristic of the CMV20000. We applied the definition of bias level -- the mean value of the median frame with the shortest exposure time acquired in darkness -- and therefore we used this higher value as bias level in the following.

Before measuring the gain, another useful diagnostic way to evaluate the performances of CMOS sensors is the column temporal noise. This is done by plotting the standard deviation of each sensor column in the median image (from the 30 images acquired) of the dark exposure with the shortest exposure time (in this case).
The column temporal noise as function of column number is shown in Figure 3 and does not present any particular difference between the two sensors. We notice a slightly larger scatter of the values for the concave sample but such values show a similar behaviour compared to the flat sensor case -- they increase at the centre and decrease at the two edges -- and they are also overall smaller.

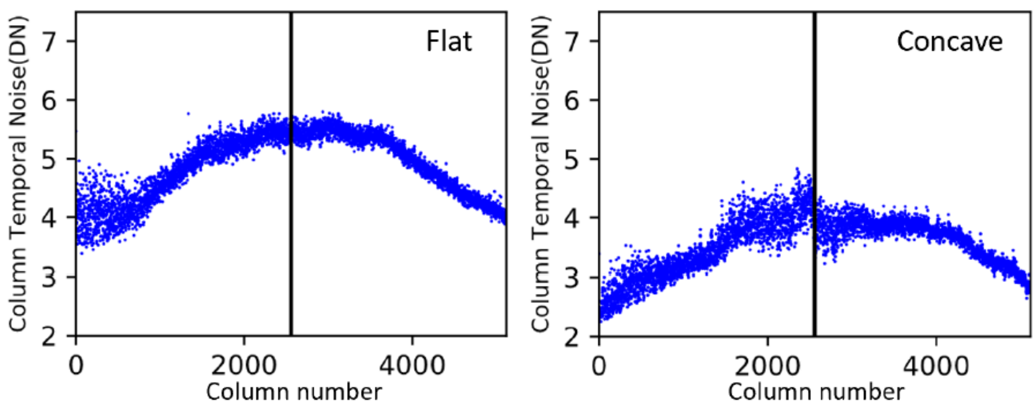

Figure 3 Column temporal noise of a median dark exposure image at 0.0002\,s vs column number for the flat (left) and the concave (right) sensors.

The gain was measured from a set of flat fields where the sensor is exposed to uniform and stable illumination. In Figure 4 the mean signals observed by the two sensors are shown vs the exposure times. The signal grows linearly for exposure times larger than 0.048s until it reaches the saturation limit of 4095DN (set by the Analog Digital Converter, as it has 12-bit per pixel) for both sensors.

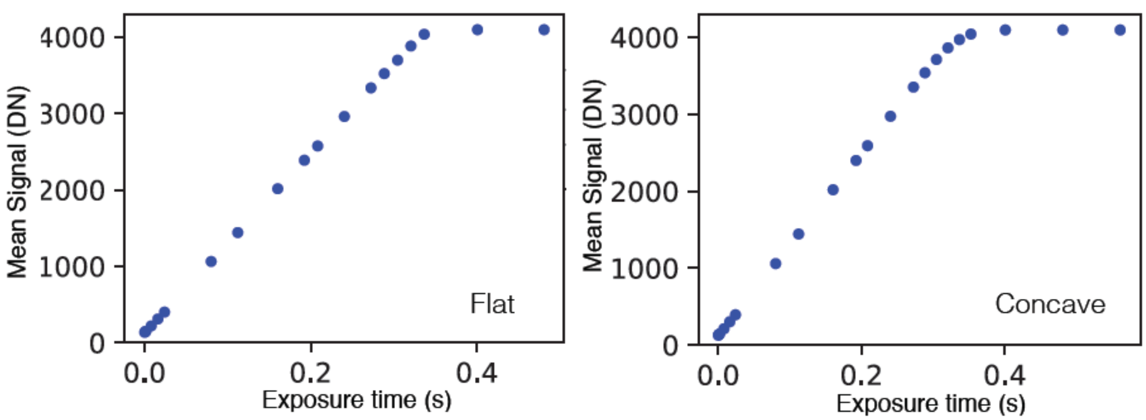

Figure 4 Mean flat field signal as function of exposure time. Left: data for the flat sensor. Right: data for the concave sensor.

In Figure 5 are plotted the squared temporal noises of both detectors against the mean signal - offset. For values of mean signal - offset between 1000DN and 3000DN we see a linear trend. From the slope of the fit to the linear part, we obtained a gain of 0.200+/- 0.002DN /e- and 0.220+/-0.003DN/e- for the concave and flat sensors respectively. This two values are apart by 10%, however we cannot conclude that this difference is due to the curving process as it might be within the manufacturing scatter. The gain quoted by the manufacturer is of 0.25 DNe, 12% larger than the gain of the flat sensor measured in this paper.

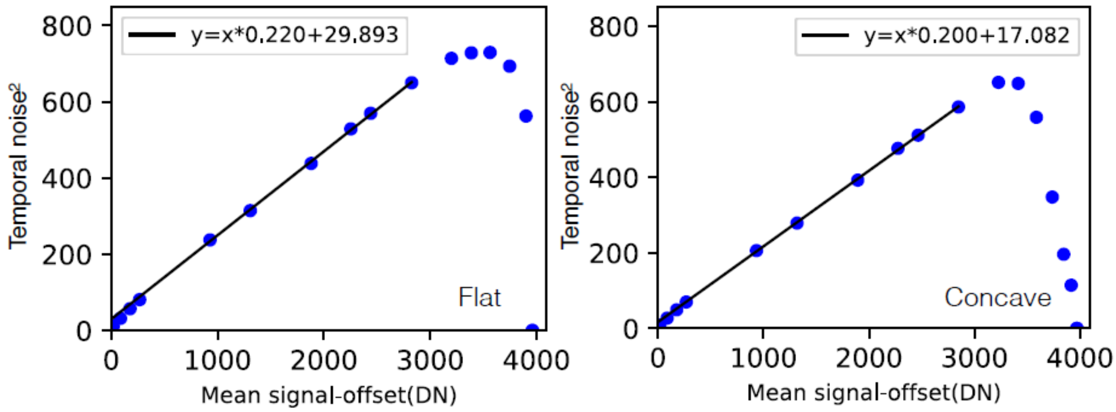

Figure 5 Squared temporal noise of flat field frames as function of mean signal-offset (bias level). The black line is the fit to the data for mean signal-offset between 1000DN and 3000DN. Left: data for the flat sensor. Right: data for the concave sensor.

In order to evaluate the noise behaviour of the two sensors, we also plotted the 2D map of the RON. This is shown in Figure 6 where we averaged the pixel values in a box of 2x2 to reduce the size of the images. We see that also the 2D map does not show any particular difference among the two. (The feature in the lower right corner of the two images is an artificial effect caused by the Evaluation Board used to control and readout the sensors.)

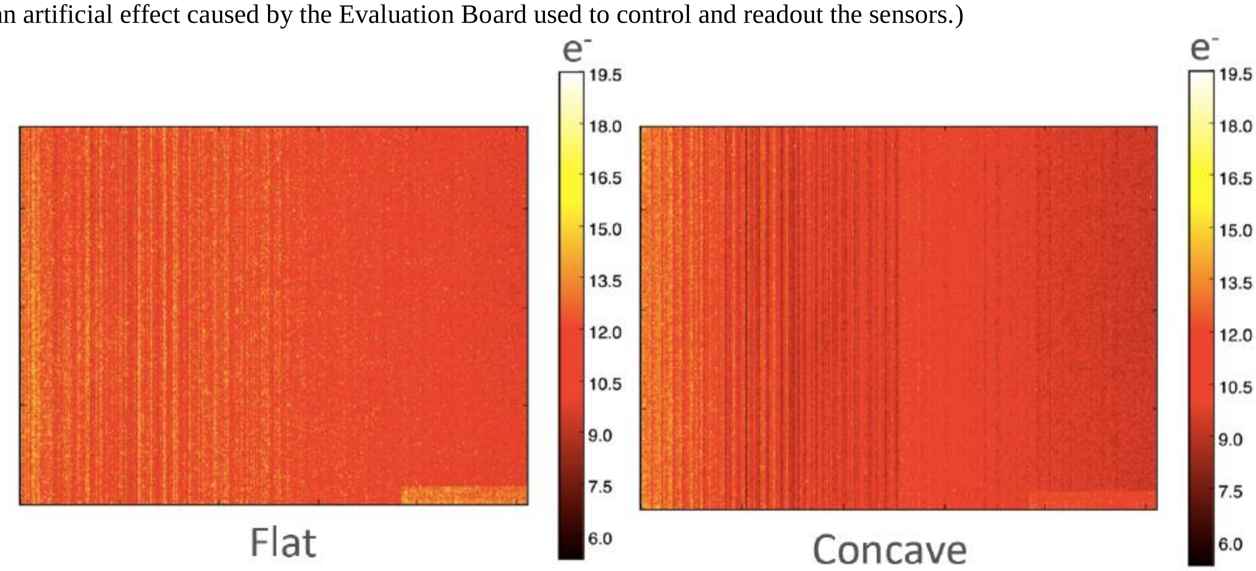

Figure 6 2D map of the RON for the flat sensor (left) and the concave one (right). The values are in numbers of electrons and are averaged in a 2$\times$2 pixels box.

All these results demonstrate the exquisite performance of the produced curved sensor. Next section presents the use of one of them in a customized optical design.

3. EXAMPLE OF THE WIDE FIELD OBJECTIVE

In this section, we present our development from the design to the realization and test of a wide field zoom camera (Figure 7): a pre-industrial prototype using a convex curved sensor with a fixed curvature. This sensor is the 20 Megapixels front-side illuminated 24x32 mm CMOS sensor presented previously. We have designed a Fisheye camera using a convex curved sensor with the same characteristics as a commercial Fisheye camera (focal length, aperture, field of view; image size) a Canon 8-15 mm F/4.

The main feature of this design is that we get rid of the field flatteners, leading to the following advantages: 1/ Reduced distortion, 2/ reduced aberrations over the field, 3/ improved sharpness by a factor of 5 on the edges, 4/ improved chromatism by a factor of 2.5, 5/ completely suppressed vignetting, 6/ no aspherical optics, and 7/ 30% less optics in the design.

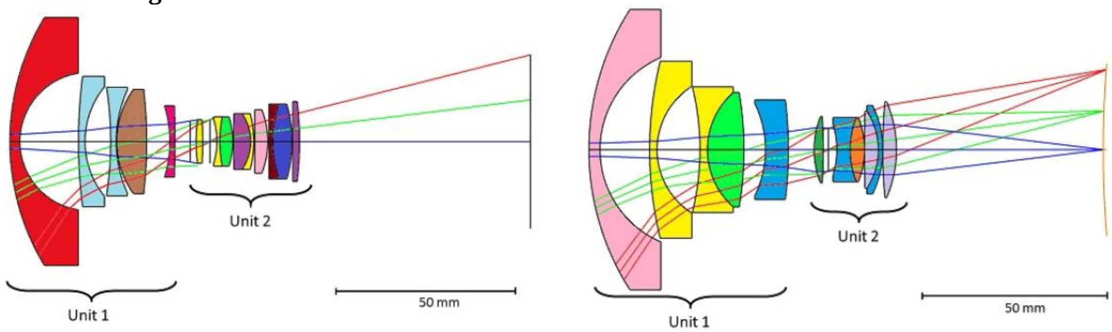

Figure 7 Optical layouts of the Canon objective [Left] and the simplified zoom camera D11L [Right]. The color code for glass materials is different for each system.

Figure 8 presents the as-built system and the pictures taken with the convex CMOS 20MPx sensor. By keeping the same characteristics as the Canon camera, we are able to quantify the gain in performance offered by the use of a curved sensor. The comparison is presented in Figure 9.

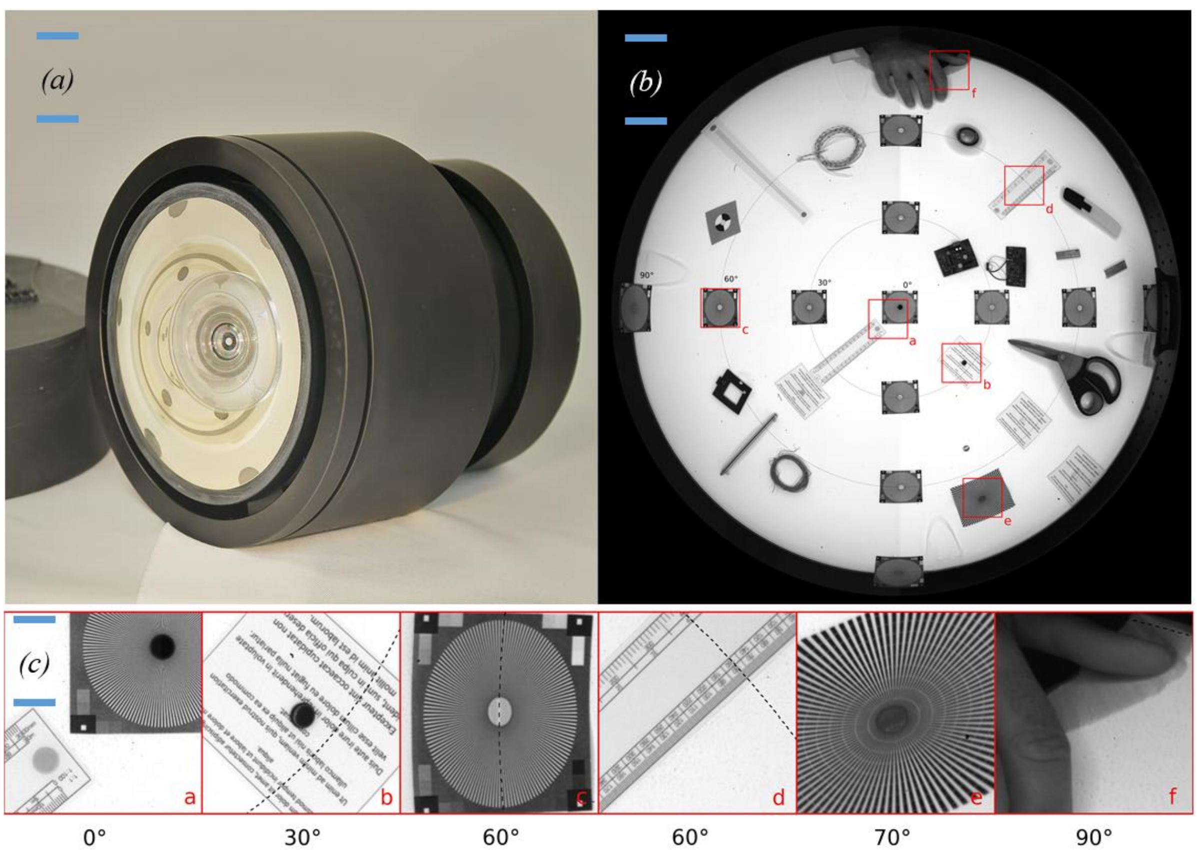

Figure 8 (a) picture of the as built 180deg FoV objective corresponding to figure 7 right. (b) 180deg picture taken with this objective combined with the convex sensor. (c) Detailed parts of the image showing the image quality over the field.

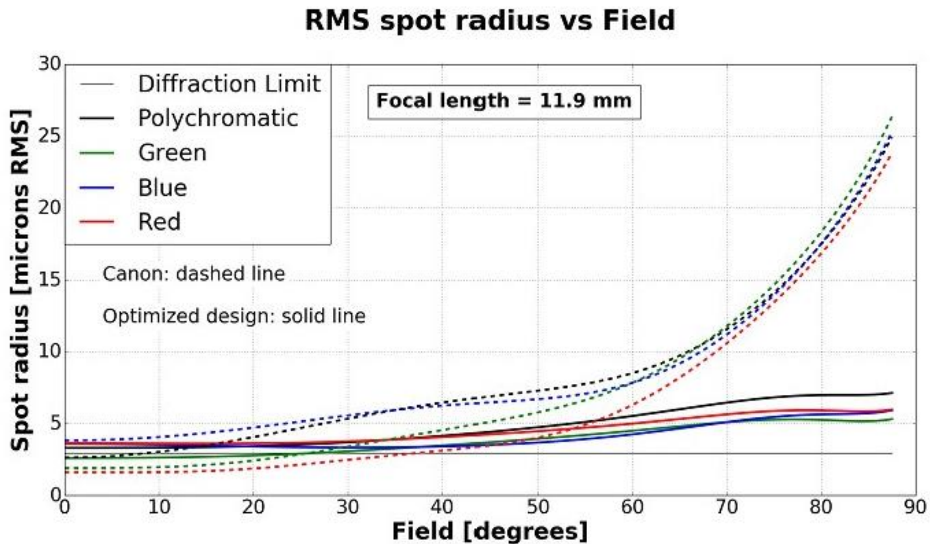

Figure 9. RMS spot radius size comparison for the two designs over the field of view. It demonstrates the obvious gain provided by the removal of the field flatteners.

4. CONCLUSION

The activity presented here gathers developments on innovative devices undertaken by CEA-LETI and CNRS-LAM as well as the demonstration of their gain in high performance optical systems designed at CNRS-LAM and prototyped. The full electro-optical characterisation has demonstrated that there is nearly no modification in the performance of the sensors if they are curved, some parameters even becoming better.

ESA and ESO already expressed their interest into developing such devices for ground based and space applications. The next steps in the developments are clear, and require the engagement of countries participating into the ESA and ESO development strategy.

5. ACKNOWLEDGEMENT

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