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Curved CMOS imaging sensor: benefits for space optical system design

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ABSTRACT

Curved imaging sensors bring significant size, weight and cost reduction to imaging systems while mitigating off-axis optical aberrations, as opposed to current flat sensors. Unlocking these key features has captured the interest of major players over the last two decades. SILINA has been developing a CMOS Image Sensor (CIS) curving process, which adapts to various sensor characteristics. This enables the design of image focal planes to various shapes to specifically maximize the optical performance of every single imaging system. We demonstrated the manufacturing of spherical and aspherical CIS in 2021, opening a new area of compact, fast, wide-angle and high-resolution optical system solutions.

From concave to convex, spherical, aspherical, cylindrical, toroidal, or even freeform shapes can be reached. These new degrees of freedom offered to CIS can significantly simplify optical systems through a reduction of the number of elements and improve optical performance in many different ways. The field of view, the contrast, the F-number can be increased while optical aberrations and distortion can be minimized. At the end, the different costs related to manufacturing, metrology, integration, and alignment are reduced. This is of great importance for applications requiring compact payload, high resolution, high transmission factor and shorter integration time.

In this paper we address the challenges caused by the adoption of curved image sensors, notably the different approaches for the adaptation of existing designs with a highlight on the optimization and tolerancing methodology. We describe our approach to enhance existing designs by including a curved focal plane, from the first analysis to the last optimization run, in order to improve key performance criteria while maintaining first order parameters. We discuss the improvement expected for space observation through a focus on a two-mirror telescope design based on the Hubble Space Telescope characteristics.

Keywords: Curved, CMOS, Design, Image Sensor, Imaging, Optical Instrument

1. CURVED IMAGE SENSOR: A KEY TECHNOLOGY FOR HIGH PERFORMANCE OPTICAL INSTRUMENT

One of the most efficient imaging system is our eye. It provides an very good image quality and sensitivity with a large field of view. Still, at a first approximation, the eye presents a really simple optical system with only one optical element : the crystalline. All these benefits come from the fact that the retina is curved.

Today, imaging systems have to be bulky with a lot of optical elements to reach high performance at the cost of a complex and expensive system. These effects come from the fact that the sensor is flat. Indeed, due to the Petzval field curvature, an extended scene cannot be into focus on a flat image plane but into a portion of a sphere. Field flatteners are inserted along the optical path to mitigate the curvature of the field but can significantly complexify the optics. Using a curved focal plane enable to remove these field flattening optical elements and can correct the field curvature while maintaining the optical performance. At the end, it reduces

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the complexity and cost of the optical system. [2]

CIS bring significant size, weight and cost reduction to imaging systems while mitigating their off-axis aberrations. Unlocking these key features captured the interest of major players of the semiconductor industry for the last two decades. Lens designs and CMOS curved image sensor manufacturing techniques have been investigated by various companies like Sony [4] or Microsoft [3] through patents and papers, and (un)cooled infrared curved sensor prototypes have also been manufactured and demonstrated functional performance.[6, 1]. Yet, the research has been limited to non-scalable single-chip processes only suitable to low-volume applications.

SILINA is a french company developing an innovative manufacturing process enabling to curve existing imaging sensors at scale. SILINA curving technology allows to curve multiple sensors at the same time, making the process scalable and reliable to benefit low volume and high volume markets. The curving process adapts to the format of the sensors, the sensor technology and the spectral bandwidth. The final targeted shape can be specifically designed and custom on-demand based on customer needs.

In this paper, we propose to compare the performance of a flat and curved focal image plane in the case of two space optical designs. First we describe the potential gain of performances allowed by the introduction of a curved CIS on an two-mirror reflective design, namely the Hubble Space Telescope (HST). Then, SILINA's curving capabilities will be briefly presented as well as the first results on shape accuracy. Finally, ongoing and future development are communicated.

2. REFLECTIVE OPTICAL DESIGN : THE HUBBLE SPACE TELESCOPE WITH A CURVED FOCAL PLANE

2.1 Specifications

Two-mirror telescope is one of the most common configuration for telescopes, as found for example on the Very Large Telescope, HERSHEL or The Hubble Space Telescope (HST). We propose to quantify the gain brought by a curved focal plane through an applied optical design study with the Hubble Space Telescope case. HST optical design is a Ritchey-Chretien telescope. The Ritchey-Chretien design is a robust choice for modern telescope as the two-mirror characteristics combines to produce no third-order spherical aberration or coma for small field of view. HST telescope has a focal of 57.6 m and an aperture of F/24. The Advanced Camera for Surveys (ACS) is composed of coupled charged devices (CCD) with diagonal field of view in the UV-NIR region (350-1100 nm) of 250"[5]. The basic configuration and optical parameters of the HST are shown in table 1.

Optical assembly parameters		Camera parameters	
Focal lenght (mm)	57600	Type	CCD
Aperture	F/24	Spectral range (nm)	350-1050
Central obscuration	0.33	Detector array size (px)	4096x4096
Mirrors diameter (primary/secondary, mm)	2400 / 281	Field of view (arcseconds)	180 x 180
Mirrors separation (mm)	4906.9	Pixel size (arcsec)	0.04

Table 1: Main optical parameters of the visible channel of the Hubble Space Telescope

2.2 Parametric optical study

2.2.1 Impact of a curved focal plane in function of the field of view

The original design is characterized by a mirror size of 2.4 m, an aperture of F/24, a focal length of 57.6 m, a field of view of 250" and a flat sensor.

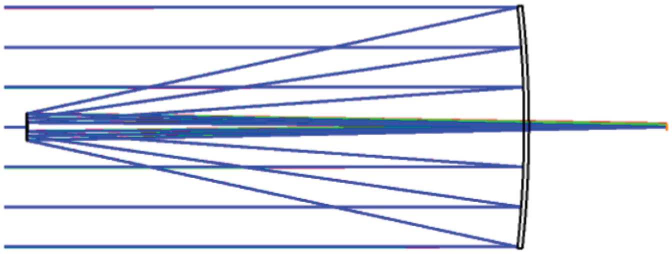
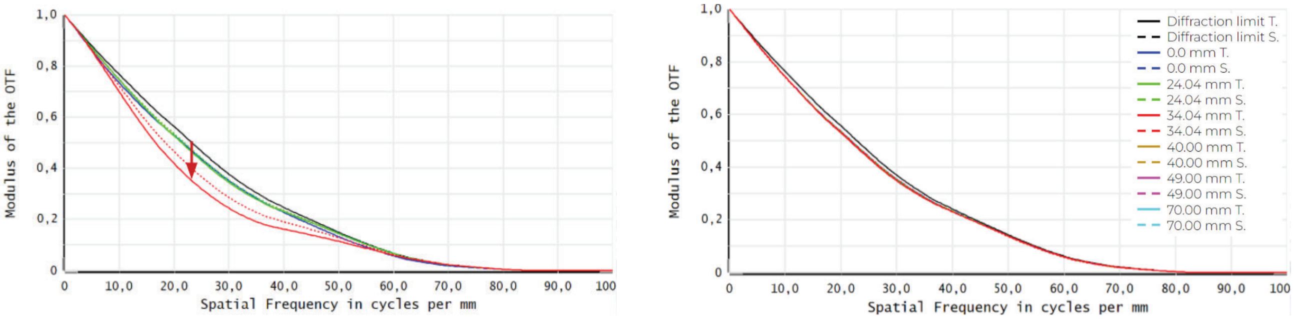


Figure 1: Optical layout of the HST

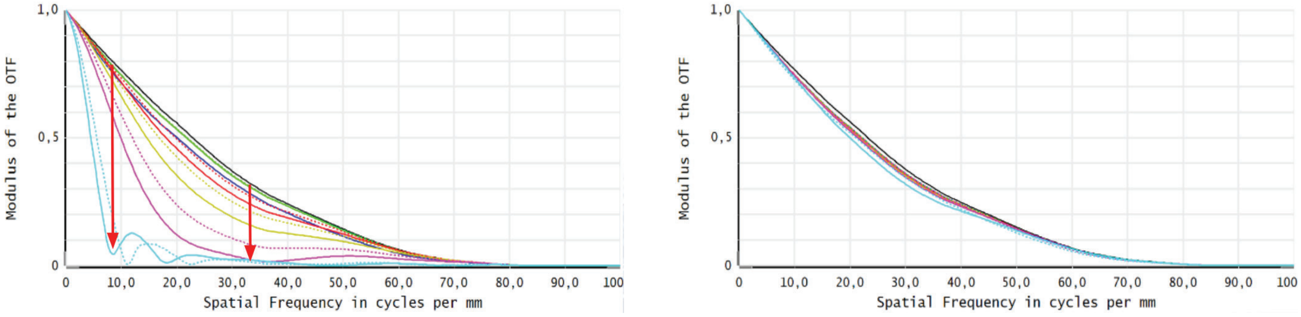
The first optical design study consists in keeping the exact same design as the current HST and replace the flat sensor with a curved image sensor at the image focal plane. We include a slightly concave image sensor, with a radius of 630 mm, at the focal surface to correct the Petzval field curvature.

Figure 2a represents the MTF of the original design of the HST with a flat sensor and a field of view of 250" on the spectral range 350-1000 nm. The performance are really good all over the field and close to the diffraction limit except for the edge of sensor which has a maximum degradation of 30%.
Figure 2b represents the MTF of the design with a concave curved sensor with a radius of curvature of 630 mm. Here the system is diffraction limited all over the field of view from the center to the edge of the sensor. This improvement of the performances of the system is only due to the new variable introduced. This shows the potential of CIS to improve current space optical designs without any modifications of the opto-mechanical layout.



(a) Flat sensor, 250" field of view

(b) Curved sensor, 250" field of view



(c) Flat sensor, 500" field of view

(d) Curved sensor, 500" field of view

Figure 2: MTF for current HST design and the one with a curved image sensor, at 250" and 500" field of view

Then, we increased the field a view by a factor of two. The purpose of this study is to quantify the impact of the curved image sensor on the modulation transfer function (MTF) when we increase the field of view. Figure 2c and 2d shows the MTF of the two previous designs but with a field a view of 500".
With a flat sensor, the MTF drops drastically and the astigmatism is exacerbated when field is increased. At

the edges, the MTF is null before a frequency of 20 cycles/mm.

It is not the case with a curved sensor, where the MTF stays diffraction limited up to the widest field of view where a maximum degradation is contained below 10%. We can note that the MTF average is better with a curved sensor with a diagonal of 500" than with a flat sensor with a diagonal of 250". Thus, while keeping an opto-mechanical assembly of iso-complexity, replacing a flat focal plane by a curved one improve the optical performances of the system and allow an increase of its field of view simultaneously.

In conclusion of this study, with a curved image sensor, the HST would be diffraction limited even with a field of view 2 times larger : we could collect more data in a smaller amount of time. As a very basic approximation, it means that Hubble could have collected the same amount of data in 8 years as he did in 32 years.

2.3 Impact of a curved focal plane in function of the aperture

The second study consists in keeping the current HST focal length (57.6 m) and field of view (250") and increase the aperture of the system. Increasing the aperture from F/24 to F/7.5 induce a change of the mirrors size. This study aims at quantify the impact of the curved sensor on the modulation transfer function (MTF) when we increase the aperture and re-optimize the system. This study is theoretical as when we increase the aperture from F/24 to F/7.5 the primary mirror diameter (which is the entrance pupil) will increase from 2.4 m to 7.68 m thus the primary mirror would be too large for a space payload, but close to the configuration of a ground-based telescope.

Figure 3 represents the MTF of designs with a flat sensor (left column) and with a curved sensor (right column). From the top to the bottom, the aperture is equal to F/24, then F/15 and F/7.5. One should note that the cutting optical frequency is more than tripled (from 83 cy/mm to 267 cy/mm)

In the configuration with a flat sensor, the MTF average drops as soon as we increase the aperture. At F/15 the loss of contrast is steep at the edges of the focal plane but the contrast and resolution are better at the center of the image. For an aperture of F/7.5, only the center field maintains a correct contrast while the rest of the field is not correctly resolved with a strong drop to 0 at around 35 cc/mm and 10 cc/mm, respectively at 70% of the full field and at the full field.

In the case of using a curved focal plane, the systems are diffraction limited over the full field of view at F/24 and F/15. When the aperture is equal to F/7.5, only the widest field is degraded with a maximum loss of 50% at 100 cy/mm.

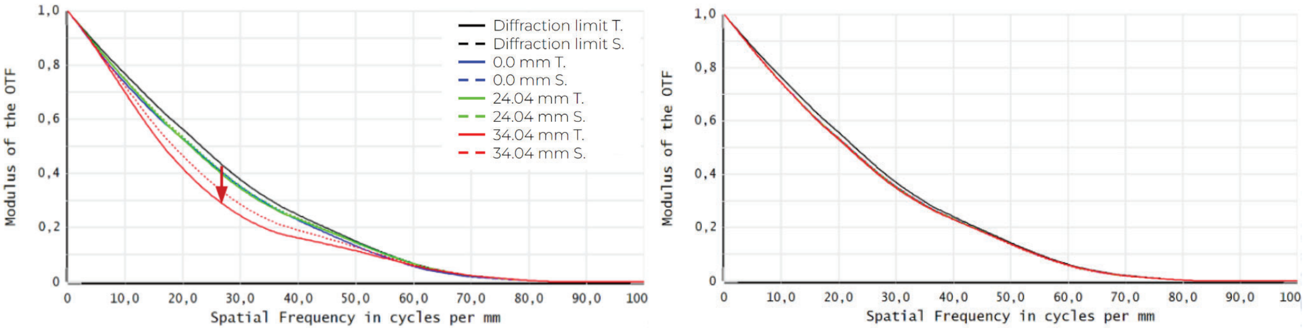
3. CMOS IMAGE SENSOR CURVING CAPABILITIES

3.1 SILINA's facilities

SILINA's technological development and production are located in Aix-en-Provence, in France. We operates in a fully equipped 700m² ISO 3 to 5 clean rooms on the microelectronics platform called Micro-Packs, dedicated to back-end semiconductor. We have access to a private area (Figure 4a) where we can operate in a complete security. We have developed our own electro-optical test-bed, EMVA compliant and fully automated (Figure 4b). We also have the capability to perform environmental tests: thermal cycling, shock, vacuum, and humidity tests (Figure 4c).

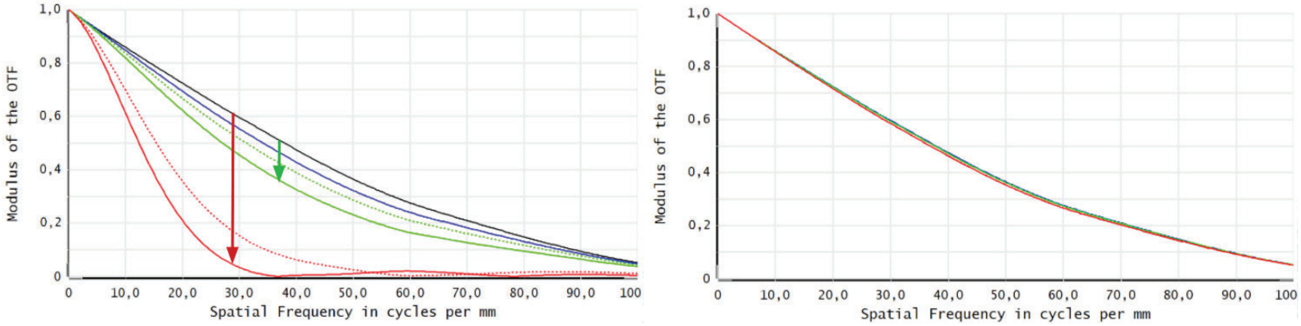
3.2 Description of the manufacturing process

SILINA does not design nor develop new CMOS image sensors but curve already existing ones. The curvature is one step added to the standard production line of an image sensor. SILINA inserts between the sensor manufacturer and the instrument developer or integrator. We can also support the various players who discuss early stage mission to help designing optical systems and assess how curved sensors can improve the imaging system.



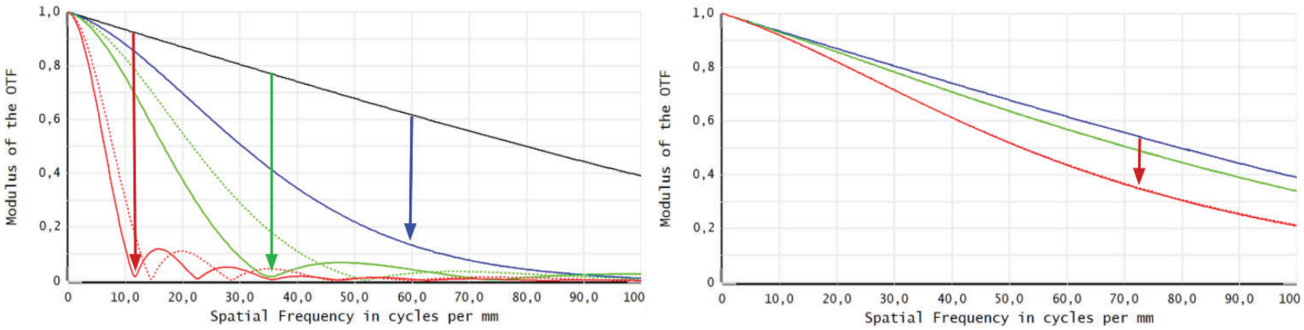
(a) Flat sensor, aperture of F/24

(b) Curved sensor, aperture of F/24



(c) Flat sensor, aperture of F/15

(d) Curved sensor, aperture of F/15



(e) Flat sensor, aperture of F/7.5

(f) Curved sensor, aperture of F/7.5

Figure 3: MTF for design with flat or curved image sensor, with an aperture of F/24, F/15 and F/7.5

The manufacturing process to obtain curved image sensors is decomposed by several steps. The first one consists of receiving wafers or bare dies, and standard packages. Then, we perform a back grinding step: the sensors are thinned in order to make them more flexible. If the wafer is complete, we perform a dicing step in order to individualized the dies. At that step, the dies are ready to be curved.

The process developed by SILINA can reach different shapes : spherical, aspherical, toroidal and custom shape based on instrument's needs. We can reach concave and convex shape but also extremely flat shape. The curving process can be applied to any format from 1/3" to full frame and even larger, either monochrom or color sensors, with or without microlenses. The process does not depend on the pixel pitch.

We have already demonstrated the capabilities on front side (FSI) and back side illuminated (BSI) CMOS sensors (Figure 5) and we are currently working on CMOS back side stacked image sensors. Once the sensor is curved, we perform the final packaging steps : the wire bonding and the integration into the ceramic with a glass lid on the top if needed. Two characterization steps occur after the curving and packaging step: we perform optical

(a) ISO 3 to 5 cleanroom

(b) EMVA compliant electro-optical testbed

(c) Thermal cycling chamber

Figure 4: SILINA's facilities

metrology to measure the shape accuracy, and we perform the electro-optical performance characterization.

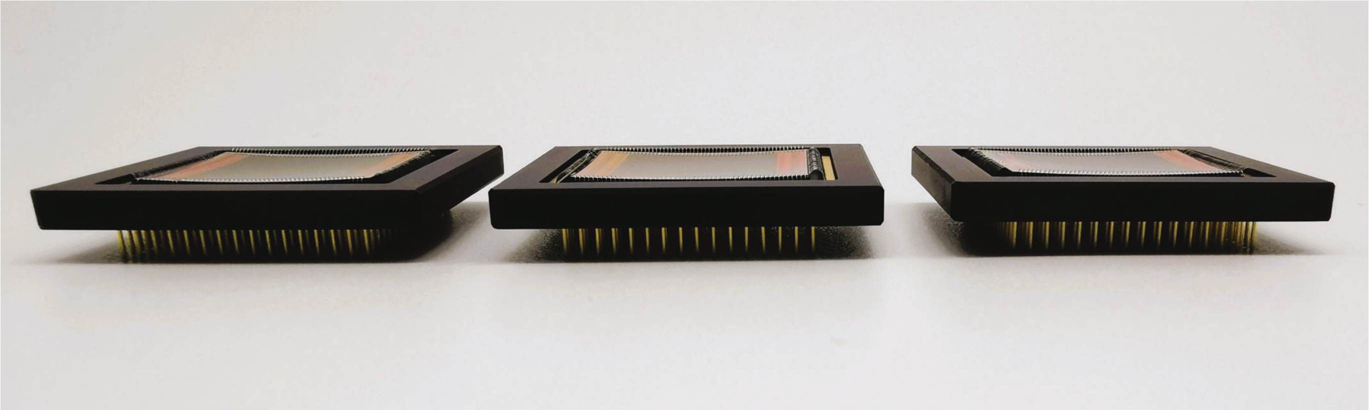


Figure 5: Curved CMOS image sensors. Format: 15.7 x 18.7 mm. Pixel pitch: 6.5 um. Radii of curvature: 100 mm, 150 mm and 250 mm.

We have demonstrated that our curved CMOS image sensors deliver the same electro-optical performance as standard flat image sensors, for different radius of curvature, notably after performing environmental test such as thermal cycling between -40°C and +100°C. Results are presented at this ICSO 2022 conference by Kelly Joaquina, System Engineer at SILINA.

4. CONCLUSION

Curved image sensor technology is the key for a new generation of imaging instruments, enhancing their performance, footprint, simplicity. Through an applied study, we quantify the impact of a curved image sensor on the modulation transfer function of Hubble Space Telescope. The optical design study shows a system that stays diffraction limited even when the field of view is multiply by two, or when the system is three times more open. More data could be collected in a smaller amount of time, with an higher flux and optical resolution.

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