

FFOCUS: A Diffraction-Limited, Fast, Compact Wide-Field VNIR Optical Payload with Curved Detector and Narrow-Band Filters

Thomas Beck^{*a}, Emmanuel Hugot^b, Paolo Sandri^a, Valery Mogulsky^a, Christian Neumann^a, Thomas Sedlmaier^a, Leonhard Griener^a, Franz Ferdinand Wieser^a, Bavo Delaure^c, Bert Geelen^c, Klaas Tack^c, Fanny Keller^d, Luca Schifano^d

^aOHB System AG, Manfred-Fuchs-Straße 1, 82234 Weßling, Germany; ^bCURVE s.a.s., 92300 Levallois-Perret, France; ^cIMEC, Kapeldreef 75, 3001 Leuven, Belgium; ^dESA ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands

ABSTRACT

The miniaturization of optical payloads represents a major challenge for next-generation space missions, particularly in the context of Earth Observation systems requiring wide swath coverage, moderate spatial resolution, and reduced mass and volume. In this contribution, we present the opto-mechanical design and current development status of a novel compact imaging payload capable of achieving a swath greater than 1000 km from an orbital altitude of 800 km, while maintaining a ground sampling distance better than 150 m. This performance is enabled by the combined use of advanced mirror manufacturing techniques, innovative detector technologies, and integrated spectral filtering solutions.

The payload is based on a compact, diffraction-limited telescope employing three powered mirrors with a fast relative aperture of F/3.5. The system operates over the spectral range from 0.4 to 1.02 μm and provides an exceptionally large field of view of 66° across-track and 1.2° along-track, with limited polarization sensitivity. Special attention has been given to controlling the angle of incidence of chief rays on the focal plane, which remains below 1° across the entire field of view, thereby ensuring a central wavelength shift below 1 nm for the spectral filters. The telescope has a focal length of 53 mm and is designed to operate with a detector featuring a 10 μm pixel pitch.

The paper also presents the prototype currently under development by the consortium, including both the telescope and the focal plane. The telescope structure is manufactured using a hybrid approach combining novel manufacturing processes with established precision machining techniques. In parallel, several curved sensor prototypes are being realized and characterized. Different HDPYX CMOS sensors have been successfully curved to a convex geometry, integrated, and tested, with the objective of their inclusion in the final imager.

Finally, we report the successful demonstration and characterization of a curved LS96 hyperspectral CMOS sensor featuring an integrated Fabry-Pérot Bragg-stack filter architecture. The sensor, developed by IMEC and subsequently curved and packaged by CURVE, represents, to the authors' knowledge, the first reported realization of a curved hyperspectral CMOS detector with integrated wafer-level spectral filtering. The results obtained demonstrate the compatibility of detector-curving processes with integrated spectral filters and constitute an important step towards compact wide-field multispectral and hyperspectral space instruments.

FFOCUS – Free Form Optics with Curved Sensor - has been designed in the frame of the ESA contract 4000146142/24/NL/FFi.

Keywords: Earth Observation, Hyperspectral, Wide Swath, SWAP Instrument, Curved Sensors, Direct Filter Deposition

1. INTRODUCTION

Earth observation missions are facing a continuous increase in performance requirements while simultaneously moving towards smaller, more agile, and cost-effective platforms. Future ocean-colour and environmental monitoring missions require the combination of large swath widths, moderate spatial resolution, high radiometric sensitivity, and multispectral or hyperspectral capabilities within increasingly constrained mass and volume budgets. These trends challenge

conventional optical payload architectures, which often rely on multiple telescope modules, large focal planes, or complex optical correction schemes to achieve the required field of view and image quality.

One of the key limitations in designing wide-field optical instruments is the achievement of a good level of correction of the aberrations all over the field of view. Correcting coma and astigmatism on a large field of view as 66 degrees can be a difficult task, having these aberrations respectively a linear and a quadratic dependence with the field, at the third order. In traditional optical systems, this difficulty is overcome by splitting the ACT field of view into two or three. While effective, this approach increases optical complexity, instrument volume, alignment sensitivity and overall system cost. Progress in detector manufacturing offers an alternative approach in which the detector geometry is adapted to the optical system rather than vice versa. From an optical perspective this means correcting all the monochromatic aberrations except the field curvature. The task of correcting the field curvature is transferred to the geometry of the image surface. To be kept in mind, the approach of bending the image surface brings to the natural consequence of not fully correcting the geometrical distortion. In fact, a full correction of the geometric distortion requires a correction of both astigmatism and of Petzval curvature, see for example the Zinken-Sommer condition. Curved image sensors make it possible to directly exploit the natural focal surface of an optical design and therefore enable a significant simplification of wide-field imaging instruments.

Recognizing the potential of the sensor curving as well as the freeform optics technology, ESA initiated the activity “Prototyping of Novel Optical Payloads using Freeform Optics and Curved Sensors” [1]. The objective of the programme is to investigate and experimentally demonstrate compact optical payload concepts that combine advanced optical architecture, curved focal-plane technologies and integrated filtering solutions. The activity specifically targets the development, manufacturing and laboratory validation of a breadboard representative of a future wide-field Earth-observation instrument.

Within this framework, the FFOCUS instrument concept has been developed including a demonstrator model to verify the technological aspects of the payload. The concept combines a fast three-mirror-anastigmat telescope with a convex curved CMOS focal plane and narrow-band spectral filtering technology. The instrument has been designed to address the demanding requirements defined by ESA for future ocean-colour observations [1], including a swath larger than 1000 km from an orbital altitude of 800 km, a ground sampling distance better than 150 m, and operation over the visible and near-infrared spectral range.

A central feature of the FFOCUS concept is the co-design of the optical system and detector geometry. The telescope generates a curved image surface that is directly matched by a convex detector, allowing diffraction-limited imaging performance to be maintained across an exceptionally wide field of view of 66°. At the same time, the optical architecture controls the chief-ray incidence angle on the focal plane to values below 0.4°, thereby reducing the spectral shift experienced by deposited narrow-band filters and enabling highly integrated focal-plane solutions.

Beyond the optical design itself, the project aims to experimentally evaluate the applicability of curved detector technologies for future compact spaceborne imaging instruments. To this end, a dedicated curved CMOS detector has been developed and will be integrated with the FFOCUS telescope breadboard to validate the wide-field optical concept concerning imaging performance. In parallel, a second technology demonstrator based on IMEC's LS96 hyperspectral sensor (based on AMS CMV2000) has been curved and characterized. This demonstrator enables the assessment of the compatibility between detector curving processes and integrated spectral filtering technologies, providing valuable insights into future compact multispectral and hyperspectral focal-plane architectures.

The paper introduces the FFOCUS instrument concept and summarizes the status of its development. Emphasis is placed on the curved detector technology and its integration with narrow-band filtering solutions. The optical design, prototype implementation and current characterization activities are presented together with their implications for future compact wide-field Earth-observation payloads.

2. FFOCUS INSTRUMENT AND BREADBOARD CONCEPT

The instrument requirements were derived from the technical specifications defined by ESA and correspond to a representative ocean-colour observation mission [1]. The selected performance targets, including a swath exceeding 1000 km, a ground sampling distance of 150 m, operation over 21 spectral bands between 400 nm and 1020 nm, and stringent

radiometric requirements, are largely inspired by the requirements defined for the Sentinel-3 Next Generation Ocean and Land Colour Instrument (AOLCI).

Meeting these requirements with a compact payload architecture constitutes a significant challenge. Conventional wide-swath ocean-colour instruments typically rely on multiple optical modules or complex optical systems to simultaneously achieve large field of view, high image quality and demanding spectral performance.

The resulting instrument architecture combines a compact three-mirror-anastigmat telescope with a convex focal surface specifically matched to a curved detector. By adapting the detector geometry to the image surface generated by the telescope, the need for additional field-flattening optics can be reduced while maintaining diffraction-limited imaging performance over a wide field of view. In addition, the optical design maintains very small chief-ray incidence angles on the focal plane, making the architecture compatible with compact narrow-band filtering concepts.

The project is validating the different technological building blocks using two complementary demonstrators. The first demonstrator consists of the FFOCUS telescope breadboard coupled to a curved CMOS detector (HDPYX300) and is primarily intended to validate the optical architecture and the implementation of a prototype curved focal plane. The system will be characterized by OHB at the end of 2026. The second technology demonstration which is intended to be highlighted with this paper is the curving of the LS96 Multi/Hyperspectral CMOS image sensor that is based on the CMV2000. The sensor is manufactured by IMEC and curved and packaged by CURVE.

3. OPTICAL DESIGN

The optical design of the FFOCUS Telescope is based on a three-mirrors-anastigmat (TMA) with three aspherical mirrors and with the aperture stop placed half a millimeter in front of the mirror M2. The detector's surface is a convex spherical surface. The TMA layout has been analyzed since the early phases of the project for its compactness and for its capability to well correct aberrations at a fast relative aperture of F/3.5. Similar wide-field reflective optical concepts have been successfully implemented or studied [2]-[4].

To achieve high image quality in the visible spectral range at the requested relative aperture of F/3.5, we selected a TMA layout obtained from modification of the Schwarzschild design in the early phase of the project. The design and optimization were performed with a standard merit function, in which we included fundamental imaging conditions, such as the Helmholtz-Lagrange Invariant and the Abbe condition for the pupils. The use of the Helmholtz-Lagrange invariant allows for evaluating the worst-case spot diagram and the worst-case wavefront error; therefore, it represents a useful sanity-check. The Abbe condition for the pupils allows achieving design robustness.

The telescope is shown in Figure 1 with its ray-tracing.

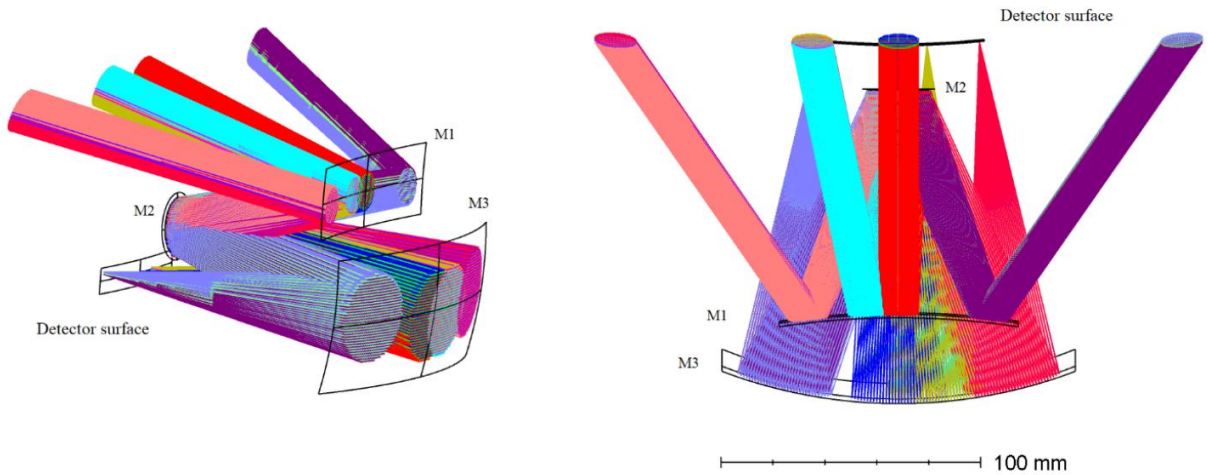


Figure 1: FFOCUS telescope design with 3D view (left) and top view (right).

Figure 2 shows a sectional view of the telescope in the ALT direction. The mirrors M1, M2 and M3 share the same optical axis. In other words, the design is rotationally symmetric and off-axis portions of the mirrors are used by selecting an off-axis angle of 21 degrees for the axial field of view. This is an important aspect of the optical design, that plays an important role not only in correcting the aberrations but also for the manufacturing phase.

The center of the sensitive area of the image surface is shifted 24.497 mm in the Y direction. The image surface is tilted 3.788 degrees.

The rotational symmetry of the telescope allows simplifying the manufacturing phase and achieving tight manufacturing tolerances. In fact, when the back sides of the three mirrors are designed to be perpendicular to the optical axis, the relative distances between M1-M2 and M2-M3 and the relative tilts can be precisely measured.

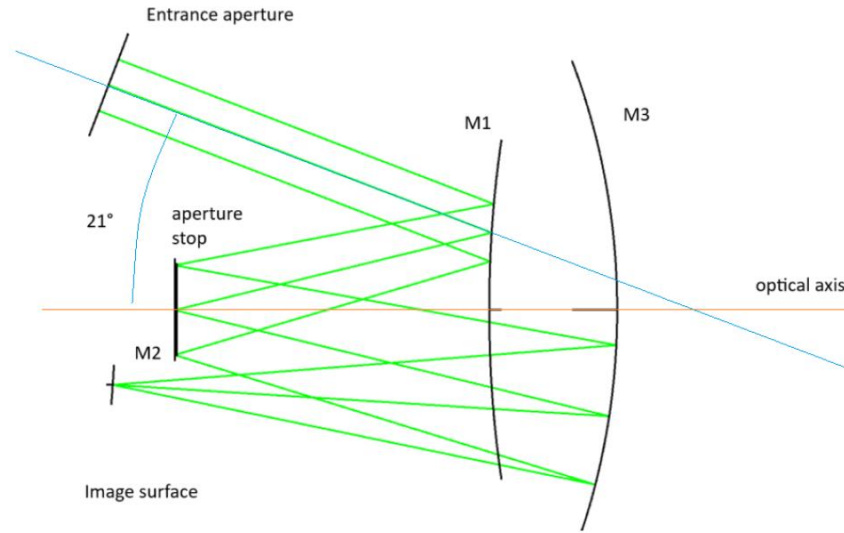


Figure 2: Cross-sectional ALT view of the telescope showing the rotationally symmetric design.

The telescope design has been analyzed in detail concerning optical performance and thus concerning (S3NG - AOLCI) instrument performance using a hypothetical curved detector with filtering. The radiometric and image quality performance requirements have largely been met. The main optical design parameters of the instrument are listed in Table 1. The nominal design is almost diffraction limited across the field of view, as shown in Figure 3.

Table 1: First order optical data of the telescope.

Optical design parameter	Value
Focal length in the X (ACT) [mm]	57.19
Focal length in the Y (ALT) [mm]	53.33
FoV ALT [°]	± 0.6
FoV ACT [°]	± 33.0
Entrance pupil diameter X [mm]	16.07
Entrance pupil diameter Y [mm]	14.97
Relative aperture in ALT, ACT	3.56
Geometrical distortion [%]	15.92

Field curvature [mm]	0.017
Worst-case chief AOI on image surface [°]	0.38
Polarization sensitivity [%]	~ 2.5



Figure 3: MTF of the nominal design of the telescope.

4. TELESCOPE PROTOTYPE

As highlighted above, the project is validating two different technological building blocks of the system separately. This chapter illustrates the prototype telescope hardware setup, the corresponding detector as well as the status of the development.

Figure 4 shows a CAD illustration of the prototype telescope which is realized within the project. The breadboard implements the optical architecture described in the previous section and preserves its key first-order characteristics, including focal length, relative aperture and curved image surface. The telescope housing is a lightweight additively manufactured structure fabricated from Scalmalloy, while critical optical and mechanical interfaces are post-machined to achieve the alignment precision required by the optical design. Additional alignment and metrology features have been incorporated directly into the structure to support manufacturing, integration and optical verification activities.

To fit within the programmatic boundaries while maintaining representative optical behavior, the breadboard mirrors do not fully implement all manufacturing steps foreseen for a future flight model. In particular, the mirror polishing and coating processes have been simplified with respect to the flight configuration. Nevertheless, the breadboard retains sufficient optical performance to experimentally validate the wide-field optical concept, the curved focal-plane architecture and the associated alignment procedures.

During the verification campaign, the focal-plane assembly will be repositioned to sample different regions of the image surface, allowing the optical performance to be assessed across the full field of view despite the use of a detector smaller than the nominal flight focal plane that would be needed to provide the full image swath.

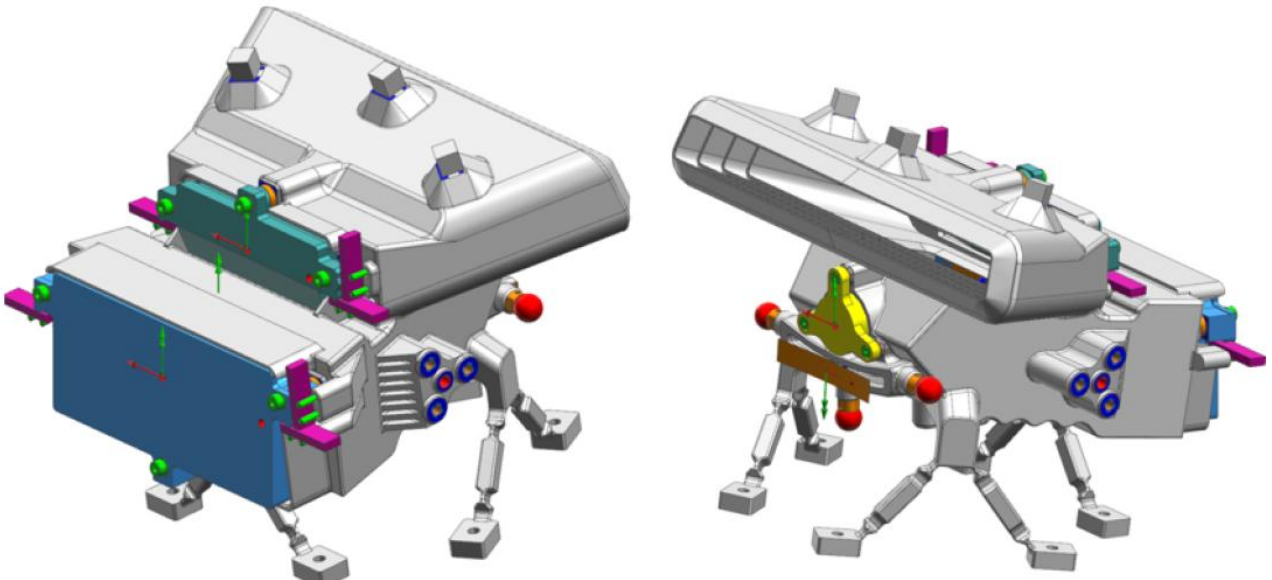


Figure 4: CAD view of the prototype telescope.

The focal-plane assembly of the telescope demonstrator is based on a curved CMOS sensor derived from the HDPYX family (HDPYX300). The selected device features a 10 μm pixel pitch and approximately 3 million pixels arranged over an active area of 28 mm $\times$ 10.9 mm.

The HDPYX sensor was selected primarily because the curving process has been previously applied by CURVE on this sensor family. This enabled the project to focus on evaluating the integration of a curved detector within a representative optical payload rather than developing a dedicated detector curving and thus reducing risks. The sensor was curved to match the focal-surface geometry generated by the telescope and subsequently integrated into a dedicated package allowing mechanical alignment and electro-optical characterization.

Unlike the hyperspectral demonstrator discussed in the following section, the curved HDPYX detector does not incorporate integrated spectral filtering functions. Its role is to serve as an imaging sensor for validation of the telescope architecture and the curved focal-plane concept.

At the time of writing, the manufacturing of the FFOCUS telescope prototype is ongoing. The telescope housing, fabricated from Scalmalloy using additive manufacturing techniques, has been produced and delivered to SpaceOptix for integration activities. In parallel, the manufacturing of the three aspherical mirrors is progressing. Following completion of the optical components, the telescope breadboard will undergo assembly, alignment and optical verification before being delivered to OHB. OHB subsequently performs the verification of the system, including the curved focal plane. Figure 5 shows a picture of the prototype telescope housing ready to be post machined and integrated.



Figure 5: Picture of the prototype telescope housing.

On the focal plane side, the HDPYX300 sensors have undergone the curving process at CURVE according to the specified curvature radius suitable for the prototype telescope. The curving process has been successful, and devices tested at the supplier. One of the devices is consequently used by OHB for telescope prototype verification. Figure 6 shows a picture of three curved devices.

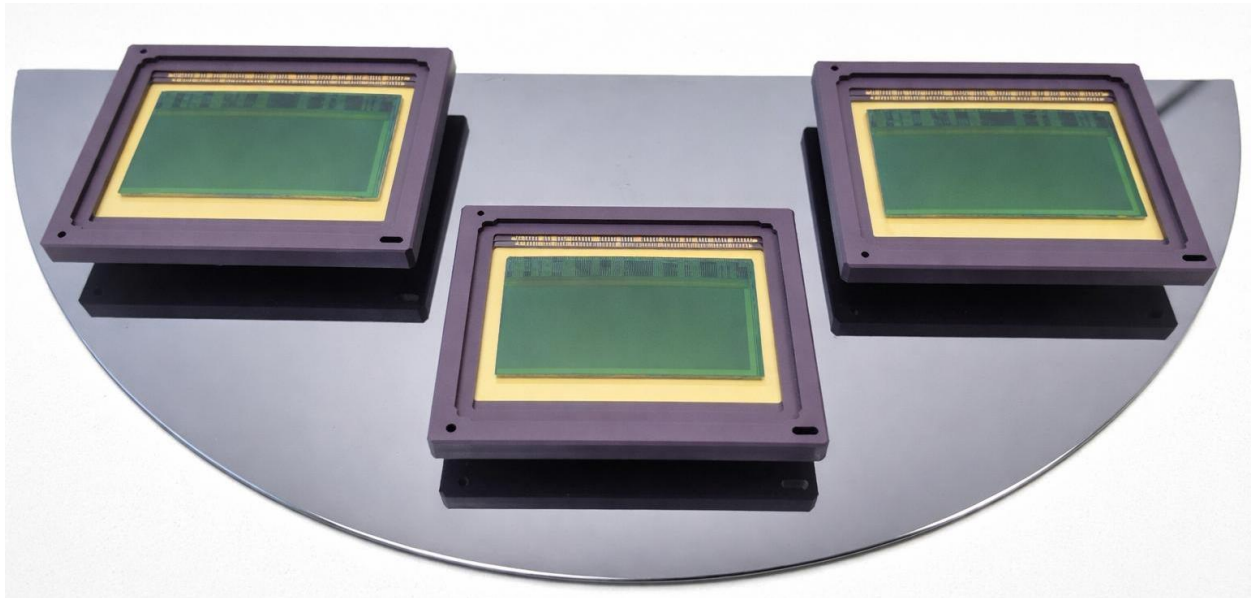


Figure 6: Curved HDPYX300 sensors.

5. HYPERSPECTRAL CMOS SENSOR

While the curved HDPYX detector described in the previous section is primarily intended to validate the optical concept of the FFOCUS telescope, the fulfilment of the AOLCI instrument requirements also requires the implementation of a spectral filtering solution. The requirement defines a multispectral instrument covering 21 spectral bands across the visible and near-infrared spectral range, making spectral discrimination an essential element of the overall payload architecture.

Consequently, the project included the development and demonstration of a filtering technology compatible with curved focal-plane concepts.

In conventional optical systems, such filtering functionality is typically realized using discrete optical filters mounted in front of the detector. For instruments employing curved focal planes, however, such an approach introduces additional complexity since the filter assembly would also have to conform to the curved geometry of the focal surface. An attractive alternative consists in integrating the filtering functionality directly at detector level. For this reason, an LS96 hyperspectral CMOS sensor developed by IMEC and based on the AMS CMV2000 image sensor was selected as a dedicated technology demonstrator [5]. The LS96 incorporates an on-chip spectral filtering architecture based on Fabry-Pérot resonators formed by dielectric Bragg reflector stacks deposited directly on the detector wafer. This architecture provides spectral discrimination at focal-plane level while eliminating the need for separate curved optical filter assemblies.

To the authors' knowledge, the application of a detector-curving process to a hyperspectral CMOS sensor featuring an integrated Fabry-Pérot Bragg-stack filter array had not previously been demonstrated. The successful realization of the curved LS96 device therefore represents a world-first achievement and constitutes a significant step towards curved focal-plane assemblies. Figure 7 shows a picture of the curved hyperspectral sensor after packaging. The radius of curvature has been, compared to the HDPYX sensor, exaggerated to challenge the limits of the detector-curving process. The radius of curvature for this demonstration has been chosen as 160mm.

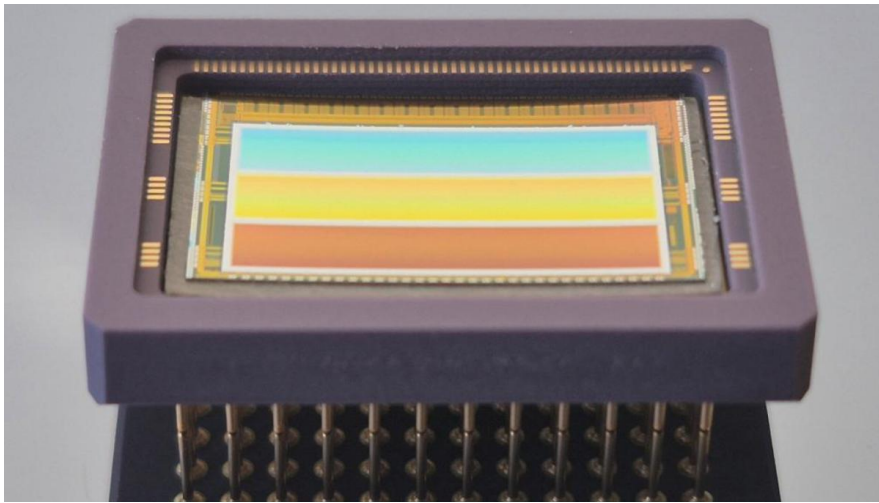


Figure 7: Image of the curved LS96 hyperspectral sensor.

The sensor has been curved and assembled at CURVE premises and provided to IMEC for detailed characterization. The characterization demonstrated that the LS96 sensor survived the curving process without any blemishes or cracks and can be calibrated using the standard calibration flow. The center wavelength's derived from the standard calibration flow are consistent with previous LS96 sensor spread statistics. The conversion gain derived from the PTC tests is typical. While the dark current is significantly higher, approximately $2.5\times$ – $3.5\times$ that of the other measured sensors, the impact of this increased dark current is expected to be acceptable due to the relatively short exposure times anticipated for the application. In addition, more recent image sensor technologies generally exhibit lower dark currents, further mitigating the impact on overall imaging performance.

6. FUTURE ACTIVITIES

At the time of writing, the hyperspectral LS96 work package has been successfully completed, including detector curving and spectral characterization. The results obtained demonstrated the compatibility of the integrated Fabry-Pérot Bragg-stack filtering architecture with the detector-curving process and therefore represent an important milestone towards curved focal-plane assemblies.

The remaining activities of the FFOCUS project are focused on the experimental validation of the telescope breadboard. Following the completion of the manufacturing phase, the telescope will be assembled and optically aligned by SpaceOptix. Once the integration activities are completed, the telescope will be delivered to OHB for performance verification and focal-plane integration.

The first step of the verification campaign will consist of wavefront error measurements of the assembled telescope to confirm the measurements performed at supplier level. Subsequently, the curved HDPYX detector will be integrated into the instrument using a 6 DoF positioning system, providing the flexibility required to accurately match the detector surface to the telescope focal surface and to sample different regions of the field of view. Figure 8 illustrates a CAD cut view of the setup with the detector (and COTS electronics) placed in the focal plane.

Following detector integration, image-quality characterization of the complete instrument will be performed. Emphasis will be placed on the measurement of the modulation transfer function (MTF) at multiple field positions across the field of view. The measured performance will be compared against the optical predictions derived from the design and tolerance analyses, providing experimental validation of the curved focal-plane concept implemented within the FFOCUS architecture.

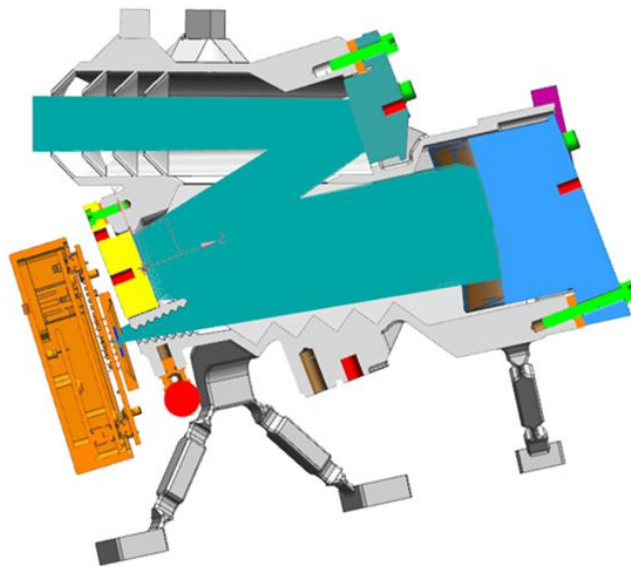


Figure 8: FFOCUS telescope prototype telescope including focal plane.

The completion of these activities will provide a comprehensive assessment of both key technological developments pursued within the project: the compatibility of curved detectors with integrated spectral filtering technologies, demonstrated through the LS96 hyperspectral sensor, and the implementation of a curved focal plane within a compact wide-field Earth observation telescope, demonstrated through the FFOCUS breadboard.

7. CONCLUSIONS

The FFOCUS project investigates a novel instrument architecture combining compact wide-field optics, curved focal-plane technologies and integrated spectral filtering solutions for future Earth observation missions. Starting from a set of requirements largely inspired by next-generation ocean-colour instruments, the activity aims to demonstrate that advanced optical and detector technologies can be combined to significantly reduce payload complexity while maintaining demanding performance levels.

The design activities performed within the project have shown that a compact optical payload featuring a 66° field of view, diffraction-limited performance, a focal length of approximately 53 mm and compatibility with 21 spectral bands can be realized using a curved focal-plane architecture. The resulting concept demonstrates that detector curvature can be exploited as an enabling design parameter, allowing the simplification of the optical system while maintaining image quality over very large fields of view. Optical analyses indicate that such architecture is capable of meeting the majority of the demanding requirements imposed on future ocean-colour instruments despite its significantly reduced size and complexity.

A major achievement of the project is the successful demonstration of curved detector technologies beyond conventional imaging sensors. In particular, the curving and characterization of the IMEC LS96 hyperspectral CMOS sensor demonstrated, for the first time, the compatibility between detector-curving processes and integrated Fabry-Pérot Bragg-stack filtering architectures. The obtained results show that highly integrated spectral filtering concepts can be combined with curved focal planes, opening new possibilities for compact multispectral and hyperspectral payloads.

Although each technological element has been investigated individually, the most important outcome of the activity is the verification of the principal building blocks required for a future optical instrument. On paper, the combination of the compact telescope architecture, curved detector technology and integrated focal-plane filtering results in a payload concept offering an attractive combination of wide swath, high optical performance and reduced volume. The project therefore provides strong evidence that future instruments may achieve performance levels traditionally associated with significantly larger payloads while benefiting from reduced system complexity and potentially lower mission cost.

Several developments remain necessary before such a concept could evolve into a flight system. These include environmental qualification of the telescope architecture, implementation of flight-quality optical coatings and mirrors, qualification of curved detector technology under thermal, mechanical and radiation environments, and the development of flight-capable readout electronics. In addition, a future operational instrument would require an enlarged focal-plane assembly, either through the development of larger curved detectors or through the implementation of accurately buttable detector modules, if the full swath shall be maintained.

The remaining activities of the FFOCUS project will focus on the assembly and alignment of the telescope breadboard, integration of the curved HDPYX detector and experimental verification of the predicted optical performance through wavefront-error and MTF measurements. Together with the successful results already obtained on the curved LS96 hyperspectral sensor, these activities will provide a comprehensive demonstration of the key technologies required to realize a future generation of compact, high-performance Earth observation payloads.

ACKNOWLEDGEMENTS

This work was performed in the frame of the ESA activity “Prototyping of Novel Optical Payloads using Freeform Optics and Curved Sensors” under ESA Contract 4000146142/24/NL/FFi. The authors gratefully acknowledge the support of ESA, and particularly the technical guidance provided throughout the activity.

The authors would like to thank the consortium partners IMEC and CURVE for their outstanding contributions to the development, manufacturing and characterization of the curved detector demonstrators and integrated filtering technologies.

The authors also acknowledge SpaceOptix for their contribution to the manufacturing, integration and alignment of the FFOCUS telescope prototype.

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