

CASPEX SWIR and Multispectral Microcameras for Space Applications

A. Antonsanti^a, C. Virmondois^a, J. Flahaut^b, M. Guenin^c, H. Baranowski^d, T. Friess^a, A. Fsian^a, N. Th  ret^a, E. Robert^a, P. Tejero-Aranguren^a, W. Durand-Mouallem^e, C. Rahbi^e, A. Djouaka-Nguimfac^e, and J. B  zine^e

^aCNES, 18 Avenue Edouard Belin, Toulouse, France

^bCNRS/CRPG Nancy, 15 Rue Notre-Dame des Pauvres, Vandoeuvre-les-Nancy

^cASTEK for CNES, 18 Avenue Edouard Belin, Toulouse, France

^dEXPLO for CNES, 18 Avenue Edouard Belin, Toulouse, France

^e3D PLUS, 408 Rue H  l  ne Boucher, Buc, France

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1. INTRODUCTION

Recent planetary exploration missions increasingly rely on compact, high-performance imaging systems to enable precise in situ analysis under severe resource constraints. Building upon the CASPEX microcamera family, jointly developed by 3D PLUS and CNES, this work benefits from technology with extensive flight heritage across multiple space missions.¹⁻⁴ CASPEX cameras have notably been operating on the Mars 2020 Perseverance rover as part of the SuperCam instrument since 2021,⁵ as well as on lunar and planetary missions and commercial satellite constellations, demonstrating their robustness and versatility in demanding environments. This work introduces a new generation of Short-Wave Infrared (SWIR) microcameras as a direct continuation of the CASPEX product line, extending its capabilities from visible imaging toward SWIR imaging. This work also presents current state of development of compact multispectral cameras based on both visible and SWIR CASPEX cameras.

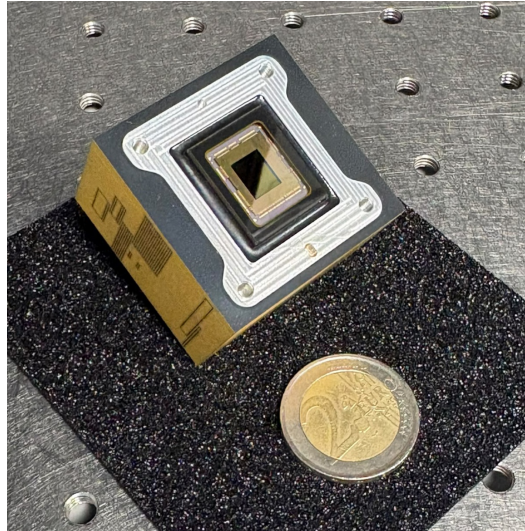


Figure 1. Image of CASPEX SWIR camera head integrating a 1.31Mpx InGaAs image sensor.

Send correspondence to A.A.

A.A.: E-mail: aubin.antonsanti@cnes.fr, Telephone: +337 62 55 33 25

2. CASPEX 1.3M SWIR CAMERA HEAD

The CASPEX camera head family has been developed by 3D PLUS in a framework of research and development activities with CNES. It integrates, within a compact module, an image sensor and the associated electronics required for its operation, providing an all-in-one optoelectronic core solution for space applications. The CASPEX 1.3M SWIR camera extends this architecture to the short-wave infrared domain by integrating an InGaAs on CMOS ROIC image sensor, sensitive from the visible to the SWIR spectral range.

CASPEX SWIR microcameras integrate a 1.31 Mpixel global-shutter InGaAs image sensor with a 1280×1024 pixel array and a $5 \mu\text{m}$ pixel pitch. The sensor provides a spectral response from 0.4 to $1.7 \mu\text{m}$. It features several integrated readout modes, including full-frame acquisition, horizontal and vertical subsampling, and Region Of Interest (ROI) readout. The sensor can operate with 8-, 10-, or 12-bit analog-to-digital conversion. In full-frame operation, acquisition rates of up to 134, 125, and 71 frames/s are available for 8-, 10-, and 12-bit operation, respectively. For reduced ROI configurations, acquisition rates of up to 3270 frames/s can be achieved.

The image sensor is controlled by a high-performance FPGA-based architecture centered on an AMD-Xilinx Kintex UltraScale KU040 FPGA. The FPGA provides the processing and control resources required for sensor operation, image handling and pre-processing, as well as high-speed communication with the user system. The architecture embeds 8 Gbit of DDR3 SDRAM for volatile processing memory and 48 Gbit of synchronous NAND Flash for non-volatile data storage. A dedicated 128 Mbit SPI NOR Flash memory is used to store the FPGA configuration bitstream. This configuration memory uses a Triple Modular Redundancy (TMR) architecture to mitigate Single Event Effects and incorporates a power-switching mechanism to improve its Total Ionizing Dose performance (TID).

Table 1. Main characteristics of the CASPEX 1.3M SWIR camera head.

Category	Parameter	Value / Description
Detector	Sensor type	SWIR (InGaAs) + CMOS ROIC, global shutter
	Resolution	1280×1024 (1.31 Mpixels)
	Pixel pitch	$5 \mu\text{m}$
	Spectral range	$0.4\text{--}1.7 \mu\text{m}$ (Visible + SWIR)
Electro-Optical Performance	Read noise	240 e^-
	Dark current	$< 30 \text{ ke}^-/\text{s}$ at 25°C
	Full well capacity	$> 170 \text{ ke}^-$
Acquisition	Frame rate (full frame)	134/125/71 fps (8 / 10 / 12 bit)
	Maximum frame rate (ROI)	Up to 3270 fps
	Readout modes	Full frame, subsampling, ROI
	Bit depth	8 / 10 / 12 bits
Electronics	Architecture	FPGA-based (user reconfigurable)
	FPGA	AMD-Xilinx KU040 ($\sim 500\text{K}$ logic cells)
	Memory	8 Gb DDR3, 48 Gb NAND Flash
Power	Consumption	$< 6 \text{ W}$ at 25°C (maximum $< 10 \text{ W}$ at 70°C)
	Supply	Single 5 V input
Environment	Radiation	TID $> 40 \text{ krad(Si)}$, SEL immune (LET $> 60 \text{ MeV cm}^2 \text{ mg}^{-1}$)
	Operating temperature	-55°C to $+70^\circ\text{C}$
	Thermal features	Integrated sensors, dedicated interfaces
Mechanical	Dimensions	$40 \times 40 \times 45 \text{ mm}^3$
	Mass	$< 140 \text{ g}$

The microcamera provides multiple LVDS and GPIO interfaces, together with JTAG and SPI interfaces, allowing the electrical interface and communication architecture to be adapted to the needs of the target imaging system. The LVDS user interfaces can be used to implement high-speed communication standards such as CameraLink or SpaceWire. All internal power supplies required by the image sensor and electronic architecture are integrated within the camera head, which operates from a single 5 V input supply. Integrated temperature sensors provide monitoring capabilities for the camera head.

The CASPEX 1.3M SWIR camera head is manufactured using 3D PLUS space-qualified stacking technology. This approach relies on the stacking of miniaturized electronic layers to achieve a high-density and compact architecture suitable for harsh space environments. The complete unit is implemented in a $40 \times 40 \times 45 \text{ mm}^3$ package with a mass of approximately 140 g. The image sensor is mounted in a metallic cradle that provides the mechanical, optical and thermal interfaces to the camera head. A dedicated copper thermal drain is also provided on the bottom of the module and is thermally connected to the FPGA and the internal power supply components.

CASPEX SWIR is designed for space applications and is available with different quality grades and operating temperature ranges. Space-grade variants are specified for operating temperatures down to $-40,^{\circ}\text{C}$ or $-55,^{\circ}\text{C}$, depending on the selected grade, with an upper operating temperature of $+70,^{\circ}\text{C}$. The CASPEX 1.3M SWIR architecture also incorporates radiation-hardening-by-design techniques. The camera head is guaranteed for a TID of 40 krad(Si) and for Single Event Latch-up (SEL) immunity up to a Linear Energy Transfer (LET) of 60 MeV.cm²/mg.

This microcamera unit addresses a broad range of applications, such as scientific exploration, Earth observation, Space Situational Awareness (SSA), and optical telecommunications. It has reached flight model maturity and is already selected both for commercial and scientific space missions, such as in the CHANCES instrument of the RAMSES mission toward the asteroid (99942) Apophis.

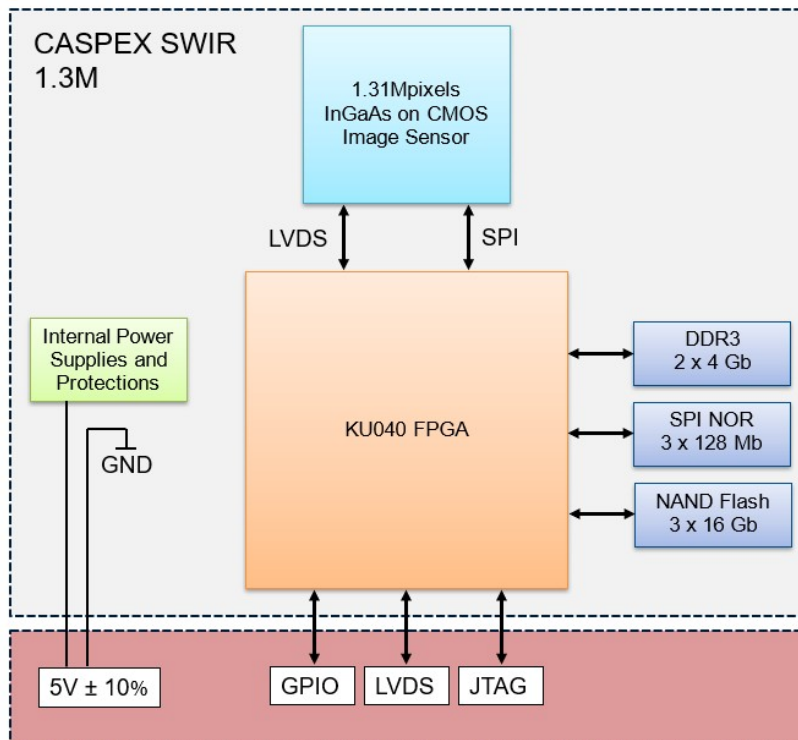


Figure 2. Simplified internal architecture of CASPEX SWIR camera head.

3. CASPEX-BASED MULTISPECTRAL MICROCAMERA DEVELOPMENT

Previous developments have demonstrated the versatility of the CASPEX camera architecture for the integration of multispectral imaging capabilities. In the framework of lunar and planetary exploration activities, two compact multispectral cameras were previously developed using customized CASPEX camera heads.⁴ The first architecture, CAM-8, relied on a CASPEX-4M equipped with a SILIOS Technologies COLOR SHADES[®]⁶ multispectral filter array, based on a 4×4 macropixel including eight panchromatic and eight spectral channels between 550 and 950 nm (Fig. 3.a). A second camera, CAM-25, was developed using a CASPEX-4M architecture equipped with a CMV2000, customized by IMEC with on-wafer multispectral filters⁷ featuring a 5×5 mosaic of 25 spectral bands covering approximately 660–960 nm (Fig. 3.b). In both cases, the multispectral layers were integrated within the existing CASPEX architecture, demonstrating the possibility of extending a compact, space-grade camera core to dedicated spectral imaging applications. These developments provide the technological basis for the ongoing activities presented in this section.

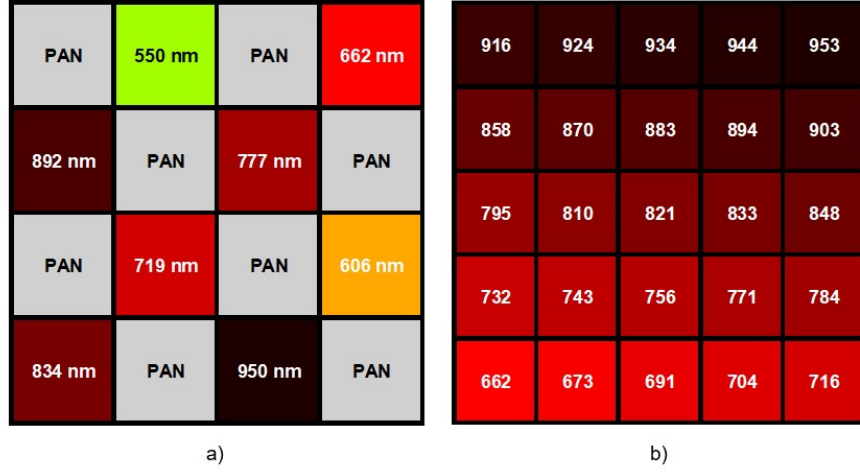


Figure 3. a) CAM-8 per-pixel filter pattern, and b) CAM-25 per-pixel filter pattern

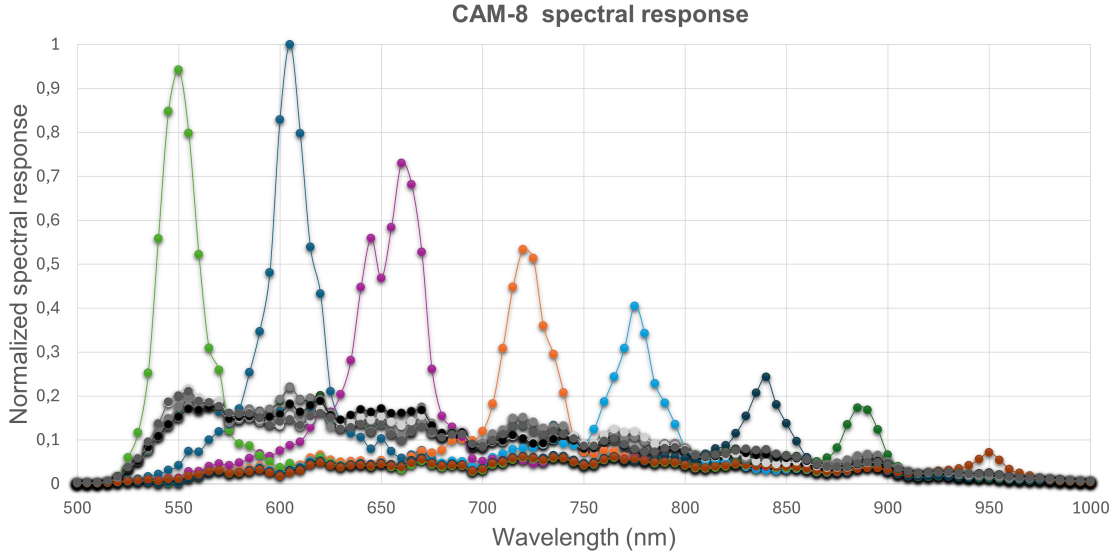


Figure 4. CAM-8 spectral response (sensor + filters + optics).

The spectral response of the Engineering Models of CAM-8 and CAM-25 described in reference⁴ (microcamera with its custom optics) were scanned using a supercontinuum laser associated with its monochromator. Results in the center of the field of view are presented in Figs. 4,5. For both cameras, the sensitivity peak of each band is within 0-10 nm of the initial specification.

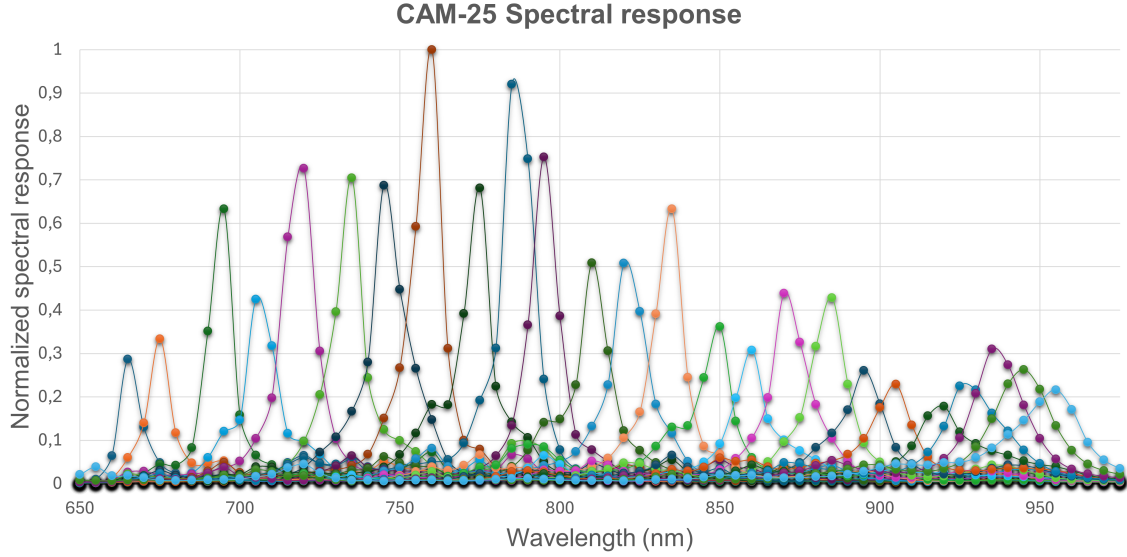


Figure 5. CAM-25 spectral response (sensor + filters + optics).

The temperature dependency of the spectral response was also evaluated using a Thermal-Vacuum Chamber in order to scan the response at -40°C , $+20^{\circ}\text{C}$ and $+60^{\circ}\text{C}$. For CAM-25, no shift of the spectral response was observed. For CAM-8, Fig 6 shows the camera's response for the three temperatures for two tested bands. It can be seen that the shift across the temperature span is smaller than 5 nm. The FWHM of the band at 882 nm seems to be affected at 882 nm. More measurements are needed in order clarify whether or not this effect is also present on other filters.

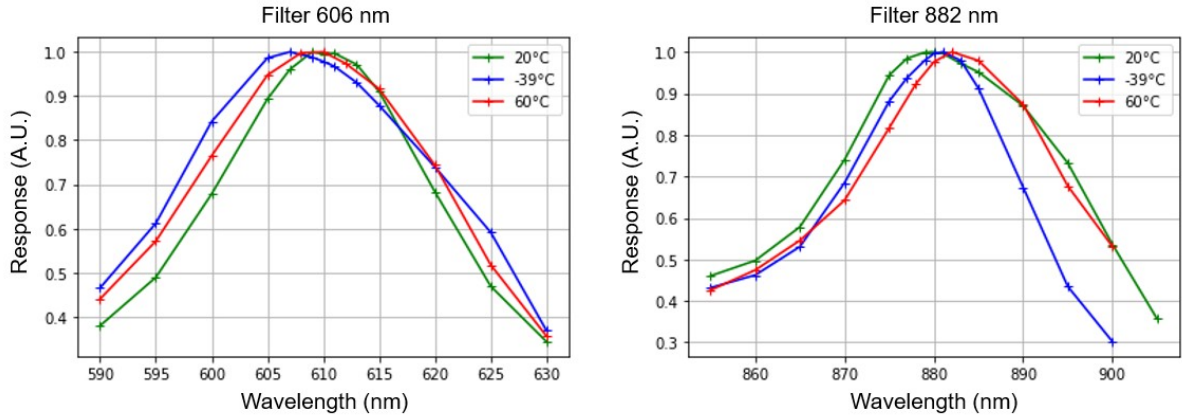


Figure 6. Temperature dependency of two spectral bands for CAM-8.

We also performed an assessment of the angular dependency of the spectral response of these visible multi-spectral microcameras. Fabry-Perot interferential filters are known to be affected by a blue shift of their spectral response based on the angle of incident light. Results for the 662 nm filter of CAM-8 are shown in Fig. 7, it can

be seen that the spectral response is indeed shifted toward small wavelengths, but also that the responsivity drops and that this angular dependency isn't perfectly symmetrical. The effect is significantly more detrimental than the effect of temperature, with shifts of tens of nanometers and sensitivity drops up to $\approx 70\%$ at large angles. Detailed results and analysis for CAM-8 can be found in reference.⁸ A similar investigation needs to be performed for CAM-25.

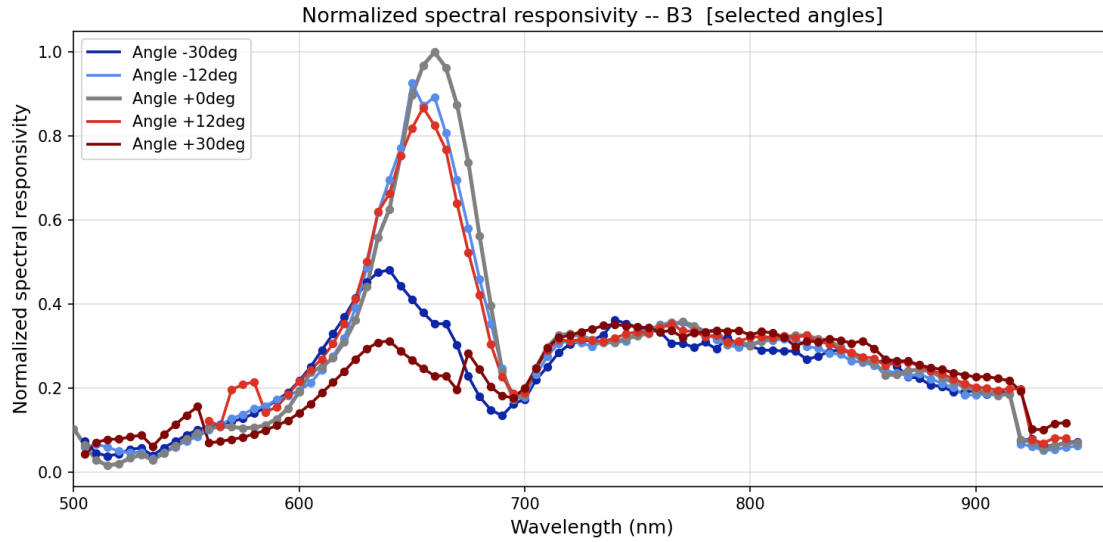


Figure 7. Angular sensitivity of the spectral response of CAM-8, band B3 (662 nm).

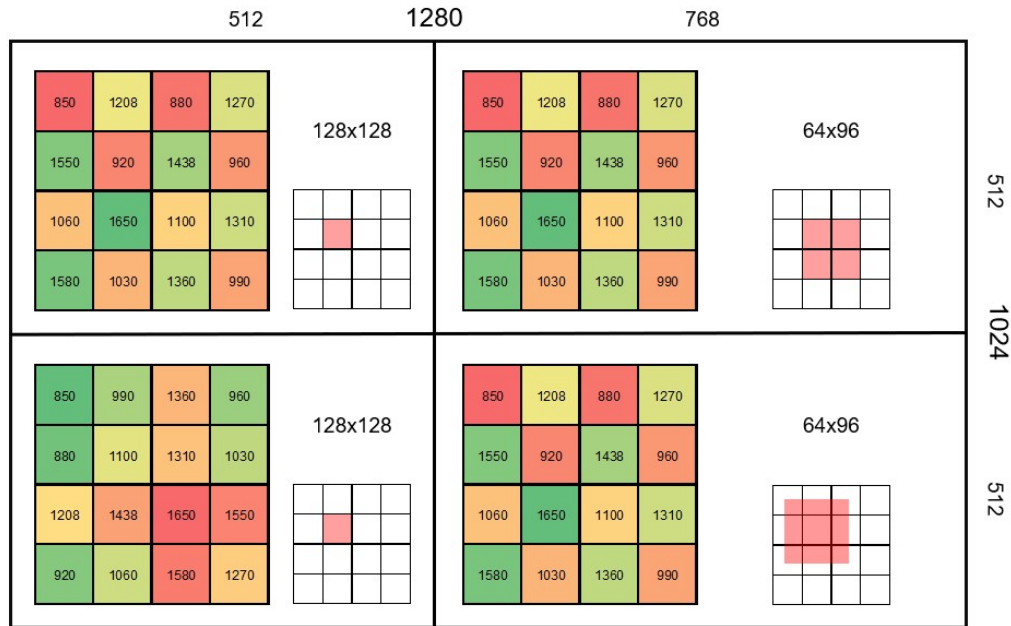


Figure 8. SFA test vehicle under investigation. The two left quadrants will be used to assess the impact of the layout of the filters in the macro pixel. The two right quadrants will be used to study the effect of binning 2x2 pixels below one filter aligned with pixels edges, or with a half-pixel shift.

Building on the success of the integration of per-pixel multispectral filter arrays (SFA) on CASPEX-4M described above, we are now developing a prototype of SWIR multispectral microcamera that will embed a SWIR compatible pixelized filter array from SILIOS Technologies on a CASPEX SWIR camera head. A 4-by-4 pattern with bands tailored to allow the identification of major rock-forming minerals on the Moon was chosen.⁹ Tests vehicles of the SWIR SFA have been manufactured according to the layout described on Fig. 8 and are currently being integrated on InGaAs sensors. The goal is to study the impact of the SFA layout as well two types of filter-on-pixel binning on the camera performance before specifying and manufacturing the final SFA that will be integrated on EMs and FM of this prototype.

To conclude, the measurements presented here aim at providing a fine calibration of the spectral response of multispectral microcameras based on per-pixel SFA, in order to unlock the best spectral fidelity possible across the field of view. It has to be noted that the quality of the final multispectral products does not only depend on accurate hardware calibration. The post-processing of the raw images in order to extract multispectral planes is also of a great importance. Efforts are thus also ongoing in order to develop an image processing pipeline that makes the most from images obtained with SFA. Recent studies¹⁰ developed a demosaicing approach optimized in order to extract high spatial resolution pseudo-panchromatic and color plane images from SFA raw images. Ongoing studies are focusing on how to best exploit the spectral information for lunar and/or martian geological analysis and mineral identification.

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