ESA STUDY CONTRACT REPORT

ESA Contract No: 4000113032/14/ NL/SW	SUBJECT: Technologies and Key Components for Compact Hyperspectral Instruments (CHIEM)	CONTRACTOR: Vlaamse Instelling voor Technologisch Onderzoek NV (VITO)
* ESA CR( )No: 4000113032/NL/ SW	No. of Volumes: 19 This is Volume No: 18	CONTRACTOR'S REFERENCE:

ABSTRACT:

D3: Executive Summary

This document contains a summary of the work performed within the entire CHIEM project. It focuses on the main results obtained.

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Version: v1.0.1

Date: 17 November 2017

CHIEM D3 - Executive Summary

Status information

Security classification:	None	State:	Final
Current version number:	V1.0.1	Date of first issue:	16/11/2017
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1 GOALS AND REQUIREMENTS

The goal of the CHIEM project was to design and build an engineering model of a hyperspectral imager, consisting of a linear variable filter and a CMOS detector, including suitable high performant read-out electronics and an optical design.

The system is designed for use in a satellite mission operating at 600km altitude, where it should be able to perform hyperspectral imaging with a swath of at least 100km, and a GSD of no larger than 25m. Moreover, the instrument should be sufficiently compact to be compatible with a 12 U CubeSat form factor.

The hyperspectral instrument is formed by Fabry-Perot type interference filters in varying thickness, each transmitting a narrow wavelength band. The filters are directly deposited on a 2D sensor array in a linewise arrangement, providing spectral information along one axis and spatial information along the other axis. The direct deposition was already successfully demonstrated in the earlier FIDELHEO project, leading to a useful hyperspectral imager with a spectral range of 475nm- 900nm, including external rejection filters (hybrid approach).

In the CHIEM project, the goal was to achieve filter deposition on a much larger sensor and at the same time improving the filter performance. The main development track was to use front side illuminated (FSI) sensors and external rejection filters. Additionally, the opportunity was taken to include two more experimental development tracks:

1) using monolithically integrated rejection filters instead of external ones
2) using back side illuminated (BSI) sensors to improve sensitivity

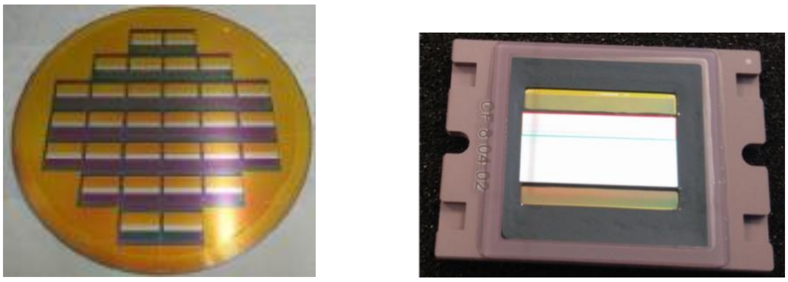

Figure 1 sensor with integrated optical filters on wafers (left) and after packaging (right)

2 FILTER DESIGN AND RESULTS

The direct filter deposition uses two filter stacks made of different materials. Each stack is completed with a fitting rejection filter blocking light outside its spectral range. The stacks are arranged in the central part of the CMV12000 sensors (4096 x 3072 pixels with 5.5µm pitch), leaving zones without filters at the top and bottom of the imager for PANchromatic imaging. The zones are clearly visible in Figure 1.

The first filter wedge covers the range from 470-620 nm, while the second wedge covers from 600 up to 900 nm, with ~20 nm overlap ensuring a smooth spectral acquisition across both ranges. The individual filter thicknesses is chosen so that the complete spectrum is adequately sampled, leading to 50 and 104 spectral bands for the respective wedges. Each band is put on 12 senor lines, resulting in total to 600 + 1248 lines for the hyperspectral zones. Two panchromatic zones without filters at the top and bottom occupy the remainder of the sensor. The depositions on the large sensor were successful, for all three development tracks.

The resulting imagers were characterized to evaluate their performance. The characterisation shows that read noise, conversion gain and full well capacity are not changed by the filter deposition, neither on FSI nor on BSI imagers. For the FSI sensors, there is no impact from the filter deposition on the dark current performance of the sensor. For the BSI sensors, the dark current increased slightly in the hyperspectral zones. Given the short integration times used, this does not impact the SNR. A larger increase was measured for the PAN zones, for this the root cause was identified so it can be avoided by a small change in the process flow.

Filter responses for the three tracks are shown in Figure 2. The top left figure shows the simulation result for monolithic integrated filters. The top right figure shows the measurement for monolithic integrated rejection filters on FSI imagers. The bottom left figure shows the measurement for hybrid integrated rejection filters on FSI imagers and the bottom right figure the measurement for a BSI imager with hybrid integrated rejection filters

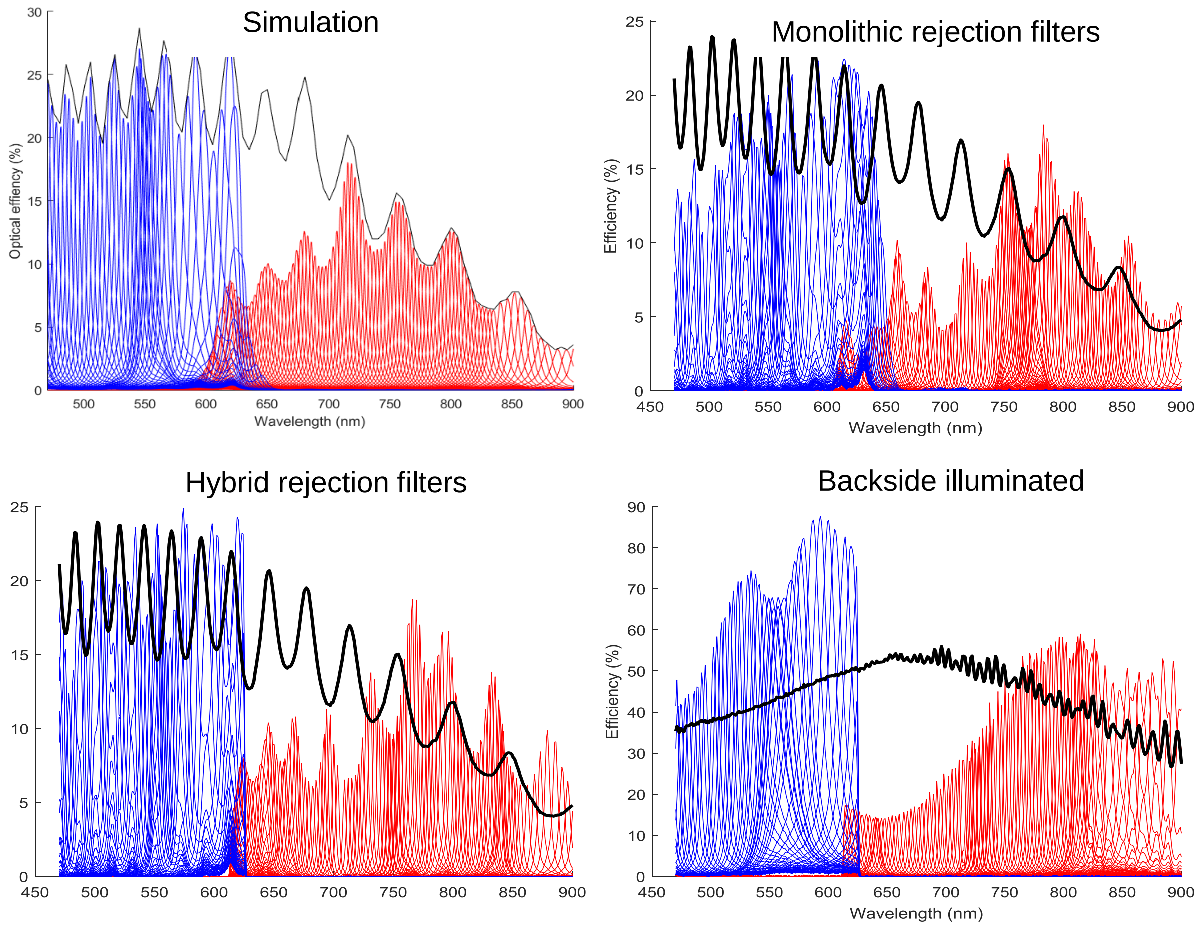

Figure 2: Comparison of filter responses

For the hybrid rejection filters, improved transmission efficiency compared to earlier results is obtained for the spectral range 600nm-700nm.

For the monolithical filters, the transmission efficiency of the filters is also good and matching the simulation. By design, backside illuminated (BSI) Sensors have a much higher optical efficiency and thus higher sensitivity compared to front side illuminated (FSI) imagers. An important gain (at least a factor 2) in sensitivity is confirmed in the results. An additional advantage of the BSI imagers is that the filter response match better with the expected Fabry-Pérot responses, as it does not suffer from interference with the BEOL with the blue filters.

Away from the peak wavelength of the filters, transmission should be minimal, so a high optical density (OD) is preferred. The highest OD is obtained with the hybrid filters, but the filters should be extremely clean and they require a more complex integration. Therefore monolithic integration is seen as the preferred route forward. The OD of the monolithical filters matches the simulations, with some variation caused by the ripple on the BEOL. The OD of the BSI imagers are lower due to the higher QE.

MTF measurements were also performed: they show that for the FSI samples (hybrid and monolithical), the filter deposition has no impact on the MTF. For the BSI , a somewhat lower MTF was expected, but unfortunately, results were much lower still, caused by shortcomings of the test setup.

3 OPTICAL DESIGN

The front telescope is a full reflective Three Mirror Anastigmatic telecentric design. This off-axis design, is very compact, completely unobscured, relatively fast (F/4.5) and offers a wide field of view in both across track and along track direction (> 9.5^o x 7.2^o).. It offers a focal length of 135 mm, with an entrance pupil diameter of 31 mm. The optical layout, shown in Figure 3, fits within a 200x200x100 mm^3 volume. M1 and M3 are strongly aspherical concave mirrors, while M2 is a spherical convex mirror. Its image quality has been optimized and achieves an MTF from 0.6 @ 470nm to 0.4 @ 900nm at 91 lp/mm (Nyquist freq. for the sensor), including manufacturing and alignment tolerances. The total transmittance is at least 80% and polarization sensitivity not higher than 1.3%.

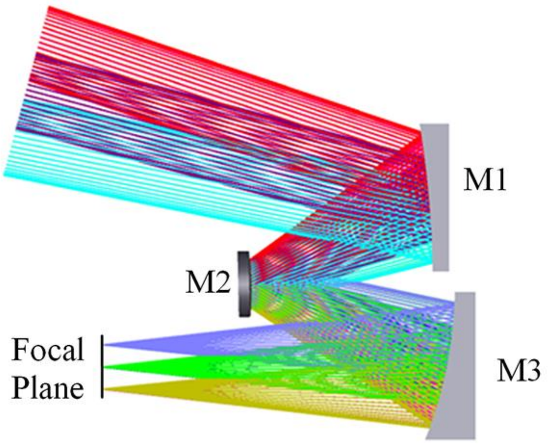

Figure 3 Optical layout of front telescope

4 READ OUT ELECTRONICS

The readout electronics (ROE) provides all required sensor interfaces enabling its full performance operation, and also a set of backend interfaces for system power, remote control, and backend remote data (to EGSE) and local storage interfaces. The challenge was to build a high performant ROE which can match the 300fps frame rate of the CMV12000 sensor. To achieve this, the design includes 64 high speed LVDS links running at 600 Mbps, for a total of useful data rate of 37.75 Gbit/s. It allows to perform following processing on the incoming data: FPN and PRNU correction, bad pixel replacement, binning, raw image accumulation for calibration map generation, and cropping. The processed data is downloaded to the EGSE using 8 high-speed 3 Gigabit Serial Digital Interface uncompressed video links (at a rate of 22 Gbit/s).

The ROE is based on the Xilinx Zynq-7000 SoC, it is modular and consists of an assembly of 3 boards:

1) *Sensor Interface Board (SI Board),* contains the sensor and the passive components
2) *Frame Grabber and Processing Board (FGP Board),* containing the SoC and peripherals
3) *External Interface and Power Board (EIP Board),* containing all interface connectors: SDI drivers and connectors, Ethernet connector and PHY, primary power connector and Micro-SD Card slot.

The ROE can operate in a recording mode recording raw frames at the highest possible frame rate and resolution. The performance achieved in this mode is 328 fps (8 bit mode), 294 fps (10 bit mode) and 130fps (12 bit mode). The ROE also supports a streaming mode to output 4K video at lower frame rates.

5 SYSTEM PERFORMANCE

The filter and sensor characterisation results confirm that the CHIEM instrument covers the 470 to 900 nm spectral range and a typical filter FWHM of 5-10 nm, matching the requirements. The sensor QE, filter transmission and the spectral resolution of the bands together determine the sensitivity of per band, which is a main driver for the performance of the system. The hybrid and monolithical filters offer similar performance. The filters on BSI are overall much more sensitive, allowing to collect more signal in the same amount of time. In all cases the large variation of the sensitivities per band, combined with the limited dynamic range of the sensor, make it important to use different techniques to increase the SNR per output pixel and obtain good signal for all bands. We list the options in order of preference:

1) **High dynamic range** (HDR)imaging: the possibility to image with two different integration times (e.g. alternating between frames) to improve the SNR for less sensitive bands
2) **Spectral binning** to a smaller number of spectral bands (e.g. 1 band per 10 nm)
3) **Digital TDI**: maximally use the available frame rate to acquire multiple acquisitions of the same location and spectral band which can be averaged
4) **Spatial binning**: only when a very high per pixel SNR is required and favored over a high spatial resolution

Note that the powerful ROE allows to acquire images at fast speeds, which allows to implement the options as listed. For the FSI sensors, the system MTF (including optical system) allows the imaging at the highest spatial resolution, while for the BSI sensors, this needs additional verification.

6 CONCLUSION

In the CHIEM project, and engineering model of a hyperspectral imager was successfully designed and built, suitable for deployment from a 12U Cubesat.

The core of the imager is formed by a set of hyperspectral interference filters deposited on a large CMOS detector. The system is completed by a read-out electronics, capable of high speed operation, which allows postprocessing techniques to improve SNR. The system also includes the design of a compact high quality optical system.

Important new results have been realized regarding the filter deposition:

- Successful deposition on large format sensors, without reducing sensor performance
- Improved filter performance (increased transmission in the critical range of 600nm-700nm)
- Successful deposition of monolithical rejection filters, without reducing sensor performance,
- Successful deposition on back side illuminated (BSI) sensors, realizing much improved sensor sensitivity

The sensors with hyperspectral filters, together with the ROE and the optical design, form a powerful system that allows hyperspectral imaging form a small space platform.

7 PROJECT PARNTERS

The CHIEM project has been carried out by a consortium of 5 companies. VITO, as prime, was responsible for the design and performance at system level and supported the development of the subsystems. Imec carried out all the work regarding the filter depositions, CMOSIS was responsible for the detectors. The design and development of the read out electronics was performed by Deltatec, while AMOS took care of the optical design.

8 SCIENTIFIC OUTPUT

4S 2016	Blommaert, J., Delauré, B., Livens, S., Nuyts, D., Tack, K., Lambrechts, A., Moreau, V., Callut, E., Habay, G., Brixhe, L., Vandenbussche, J., Minoglou, K., Deep, A, *CHIEM: the development of a new compact hyperspectral imager*, Proc. Small Satellites, System & Services Symposium (4S), At Valletta, Malta, May 30- June 3, 2016.
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EOSummit 2017	Blommaert, J., Delauré, B., Livens, S., Nuyts, D., Van Achteren, T., Tack, K., Lambrechts, A., Moreau, V., Callut, E., Habay, G., Vanhoof, K., Caubo, M., Vandenbussche, J., Minoglou, K., Deep, A., CHIEM: *A new compact camera for hyperspectral imaging*, Proc. Earth Observation Summit 2017, Montreal, Canada, June 20-22, 2017.
Smallsat 2017	Blommaert, J., Delauré, B., Livens, S., Nuyts, D., Tack, K., Lambrechts, A., Moreau, V., Callut, E., Habay, G., Vanhoof, K., Caubo, M., Vandenbussche, J., Deep, A., Minoglou, K., *CHIEM: A new compact camera for hyperspectral imaging*, Proc. 31st Annual AIAA/USU Conference on Small Satellites, Logan, UT, USA, August 5-10, 2017
Toulouse 2017	Tack, K., Gonzalez, P., Spooren, N., Lambrechts, A., Blommaert, J., Delauré, B., Livens, S., Nuyts, D., Minoglou, K., Deep, A.,*CHIEM: a hyperspectral image sensor for the miniaturized earth observation instrument CHIEM*, Proc. Workshop CMOS Image Sensors for High Performance Applications, Toulouse, France, November 21-22, 2017.