# Thin-film optical pass band filters based on new photo-lithographic process for CaSSIS FPA detector on Exomars TGO mission: development, integration and test

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## ABSTRACT

A new technique based on photolithographic processes of thin-film optical pass band coatings on a monolithic substrate has been applied to the filters of the Focal Plane Assembly (FPA) of the Colour and Stereo Surface Imaging System (CaSSIS) that will fly onboard of the ExoMars Trace Gas Orbiter to be launched in March 2016 by ESA.

The FPA including is one of the spare components of the Simbio-Sys instrument of the Italian Space Agency (ASI) that will fly on ESA's Bepi Colombo mission to Mercury. The detector, developed by Raytheon Vision Systems, is a 2kx2k hybrid Si-PIN array with a 10 µm pixel. The detector is housed within a block and has filters deposited directly on the entrance window. The window is a 1 mm thick monolithic plate of fused silica. The Filter Strip Assembly (FSA) is produced by Optics Balzers Jena GmbH and integrated on the focal plane by Leonardo-Finmeccanica SpA (under TAS-I responsibility). It is based on dielectric multilayer interference coatings, 4 colour bands selected with average in-band transmission greater than 95 percent within wavelength range (400-1100 nm), giving multispectral images on the same detector and thus allows CaSSIS to operate in push-frame mode.

The Field of View (FOV) of each colour band on the detector is surrounded by a mask of low reflective chromium (LRC), which also provides with the straylight suppression required (an out-of-band transmission of less than $10^{-5}$/nm). The mask has been shown to deal effectively with cross-talk from multiple reflections between the detector surface and the filter.

This paper shows the manufacturing and optical properties of the FSA filters and the FPA preliminary on-ground calibration results.

**Keywords:** space instrumentation, optical coating, passband filter, detector, remote sensing, photolithography,

## 1. INTRODUCTION

CaSSIS is the Colour and Stereo Surface Imaging System onboard the ESA ExoMars Trace Gas Orbiter, launched in 14th March 2016 to reach Mars in Oct 2016

The strategy to obtain colour images using the push-frame imaging approach also follows the one used on SYMBIO-SYS and is based on the capability of the CMOS detector to acquire framelets in up to six user-defined windows simultaneously [1]. An array of discrete stripe colour filters is thus installed in front of the detector, with their long-axes perpendicular to the ground-track direction. Framelets are acquired from pixels exposed by each filter with a repetition rate synchronized to the ground track velocity and set to obtain sufficient overlap between successive framelets to permit accurate mosaicking.

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The overall dimensions of the filter strip assembly (FSA) from Simbio-Sys have been conserved but the number, dimensions and positioning of the filters within the window have been modified to reflect the differences in imaging operation, optical design, and scientific aims of the Simbio-Sys and CaSSIS instruments. The field-of-view of CaSSIS, the ground-track velocity of TGO, the signal-to-noise budget and internal bottlenecks in the data transmission rate result in an optimal use of the detector area with four different colour filters and the simultaneous acquisition of up to three framelets with a maximum size of 2048x280 pixels, at a repetition rate of 367 ms. A broad transmission filter, PAN, was selected to provide the highest signal and will be used for stereo reconstruction. In our baseline configuration, 280px-high framelets will be acquired through this filter in order to have a 15% overlap between successive acquisitions. The framelets acquired through the three other colour filters will be 256px high, resulting in a 5% overlap. Data through the PAN filter are acquired on both observations in a stereo run to provide the stereo pair. The colour framelets (including binning) can be chosen to optimize the science return within the data volume constraint [2,3]. In the following Tab. 1 the main optical data are reported.

Table **1** CaSSIS filters passband data

| **Optical data** | | |
|---|---|---|
| Focal length | 880 (+/-50) mm | 871.5 mm |
| Aperture diameter | 135 mm | 135 mm |
| Nominal F# | 6.52 | 6.46 |
| Pixel size (square) | 10 µm | 10 µm |
| Angular scale | 11.36 µrad /px | 11.47 µrad/px |
| Rotation axis-boresight angle | 10.0 (+/- 0.2)° | 9.89 (+/- 0.10)° |
| Stereo angle from 400 km altitude | 22.39° | 22.14° |
| Rotation time (180° rotation) | 15 s | |
| Nominal slant distance to surface | 406.92 km | 406.76 km |
| Scale at slant angle | 4.62 m/px | 4.67 m/px |
| Time between stereo points along track | 46.91 s | 46.38 s |
| **Detector and Images data** | | |
| Bits per pixel | 14 (returned as 2 byte integers) | 14 |
| Maximum dwell time (1 px of smear) | 1.51 ms | 1.52 ms |
| Detector size | 2048 x 2048 px | 2048 x 2048 px |
| Image size | 2048 x 256 px | 2048 x 280 px (PAN)<br>2048 x 256 px (colours) |
| # of images returned per exposure | 4 | 3-6 (small windows used as dark current/bias validation) |
| Detector area used | 2048 x 1350 | 2048 x 1291 |
| FOV of used area | 1.33° x 0.88° | 1.35° x 0.85° |
| Nominal image overlap | 10% | 5% |

The high speed imaging necessary and the scientific requirement for colour information from CaSSIS dictated that, as with Simbio-Sys, fixed filters directly above the detector surface should be implemented. Instead of butted and glued individual filter strips that were initially considered, the solution is to use a single, rad-hard, fused silica, substrate with precise direct deposition of bandpass filters. The innovative technique developed by Optics Balzers is based on photo-lithography technique to deposit thin-film passband optical filters and black masks made of low reflective chromium (LRC) on a single fused silica monolithic substrate [4] allows to define the FSA areas.

# 2. THE CASSIS FILTER

## 2.1 Pass band Requirements

The wavelength bands for the four colour filters of CaSSIS were derived from the ones used on the HiRISE/MRO instrument. The two first bands, BLU and PAN correspond closely to the first two bands used by HiRISE ("BG" and "RED", respectively) ensuring consistency between the CaSSIS and HiRISE datasets. The two other CaSSIS filters, RED and NIR, split the third filter of HiRISE ("IR") in two. This additional colour is designed to improve the discrimination between expected surface minerals, particularly Fe-bearing phases, as electronic transitions and crystal field effects are responsible for strong and diagnostic absorptions in the 0.7-1.1µm range by minerals containing ferrous iron Fe2+ (mafic minerals olivine and pyroxene) and ferric iron Fe3+ (hematite, goethite…). The wing of the saturated UV absorption band caused by the Fe charge-transfer also strongly affects the spectrum at shorter wavelength, which will affect the BLU/PAN ratios. As the reflectivity of the Martian surface at blue and green wavelengths is very low, the BLU filter provides extremely high sensitivity to fog and surface frost.

Table **2** CaSSIS filters passband data

| **Filters (effective wavelength/equivalent bandwidth)** | **Designed central wavelength (nm)/ bandwidth (nm)** |
|---|---|
| PAN | 675 nm / 250 nm |
| BLU | 485 nm / 165 nm |
| RED | 840 nm / 100 nm |
| NIR | 985 nm / 220 nm |

## 2.2 Geometry and mask design

The dimensions of the filters to be applied on the window were derived from the framelet sizes on the detector and the nominal F# of the instrument. The filter is 25.0 mm x 26.0 mm x 1 mm. A distance of 200 µm was left between the filters in order to prevent ghosting and cross-talk between them and covered with the mask allowing reach an out-of-band rejection > $10^{-5}$/nm over the entire CaSSIS wavelength range (400 nm-1100 nm). Further straylight reduction was incorporated by using black masks between the filters and an anti-reflection coating while keeping all filters within the field-of-view of the telescope with sufficient margin. The chosen distance between the filters guarantees that any incident ray falling into one filter would need to be reflected at least twice on the black mask and/or the detector surface before reaching another filter area.Fig.1 shows the sequence of the mask and coating on the Fused Silica substrate.

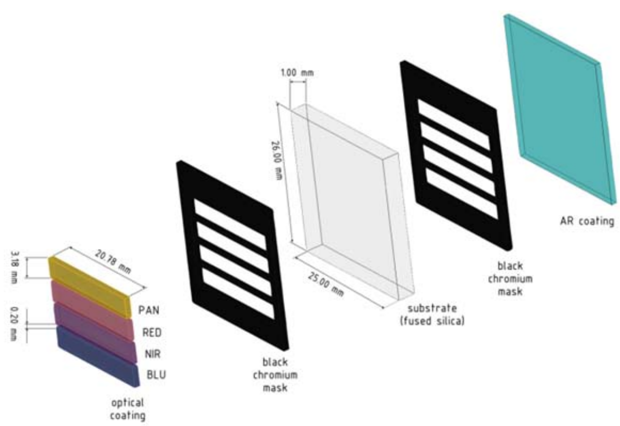


Figure 1 Exploded view of the structure of a filters array showing the four bandpass filters on the left side and the broadband anti-reflection coating on the right side. Black chromium masks are deposited between the fused silica substrate and the coating, on each side, to reduce ghosting and crosstalk

As the anti-reflection surfaces used have an average reflectivity of the order of a few percent, a double reflection means that possible artefacts would be limited to a maximum of 0.1% of the actual image signal. In addition, the area of the detector correctly illuminated behind each filter is about 310 pixels high, which leaves a margin of 15 pixels on each side in case the area read is 280 pixels high and a margin of 27 pixels in case the area read is 256 pixels high.
4 fiducials markers (1mmx 200 microns) suitable for alignment of the FSA inside the detector holder are designed, as Fig. 2 shows.

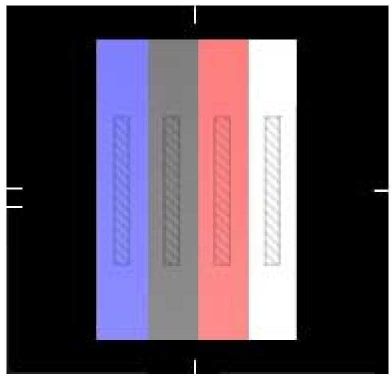

Figure 2 The central area of each bandpass filters FSA used to measure the transmission of CaSSIS PFM. The black line of mask that separates the filters is visible only from the back side where AR coating is deposited and the four markers suitable for the filter alignment are not covered.

### 2.3 Manufacturing process and performances

The manufacturing process is based on the new photo-lithographic technique developed by Optics Balzers in Jena.

All dielectric coatings are applied in a sequential processing on the same wafer substrate one after the other by micro-structured coating manufactured by using ion assisted deposition by Advanced Plasma Source (APS).
The accuracy for the layers thickness control is in the order of 0.5 nm as absolute value over the complete deposition process under stable conditions. After completion of the filter coating sequence the wafers were singularized by a dicing step. The alignment marks applied during the first photo-lithography step allow an accurate positioning. A chamfer can be applied to prevent edges from damage during further processing.
The physical properties of the manufactured filters were measured and the compliant matrix compiled to select the PFM filter. Five space-qualified filters array windows were produced. The filter selected for integration on the PFM model, "assembly_10-5", is based on the minimum number of defects (pinholes and black chromium residual) identified on all four filters of the array. The selection is based on the transmission properties, physical dimension and the minimum number of defects according with ISO 10010 (pinholes and defects of mask).
These measurements were performed by Balzers (Optics Balzers Jena GmbH) prior to shipment of the filters to the University of Bern. The numbers shown below the filter names for BLU, PAN and RED are the central wavelengths for these three filters, calculated from the filter edges, defined here by 50% of transmission. This number is not defined for the NIR filter as the long wavelength edge was not measured. The resulting measured transmittance of the 4 filters in following Tab.3 is reported and in Fig.3 is shown.

Table 3 Data obtained from spectral measurements. The band is defined at 50% of the cut off of the measured transmission.

| Filter | 50% short | 50% long | FWHM | Central Wavelength (nm) |
|---|---|---|---|---|
| PAN | 552.28 | 800.76 | 248.49 | 676.52 |
| BLU | 394.07 | 567.00 | 172.93 | 480.54 |
| RED | 786.71 | 889.28 | 102.57 | 837.99 |
| NIR | 866.86 | | *220.00* | *985.00* |

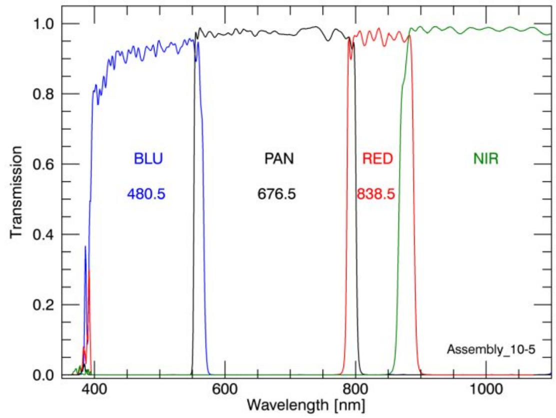


Figure 3 Measured transmission curves through the centres of each of the bandpass filters of assembly 10_5, which was then integrated on CaSSIS PFM. These measurements were performed by Balzers (Optics Balzers Jena GmbH) prior to shipment of the filters to the University of Bern. The numbers shown below the filters names for BLU, PAN and RED are the central wavelengths for these three filters, calculated from the filters edges, defined here by 50% of transmission. This number is not defined for the NIR filter as the long wavelength edge was not measured.

An example of a defect in the PAN filter caused by the Low Reflecting Chromium (LRC) mask detaching during the development of the PFM filter is shown in Fig. 4 (50 microns of LRC mask is clearly visible at microscope in transmission the close to the mask border).

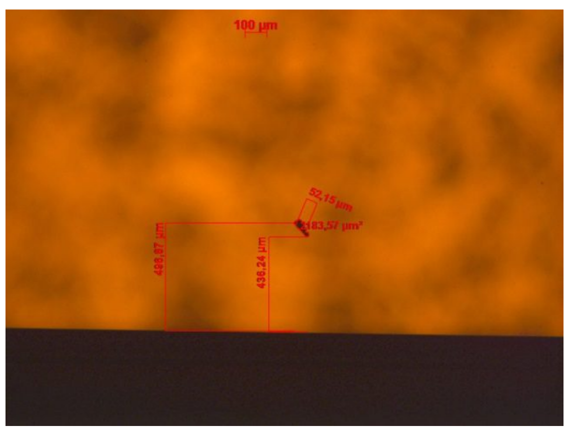


Figure 4. Black chromium masks are deposited between the fused silica substrate and the coating, on each side, to reduce ghosting and crosstalk. Small defects of black chromium can be identified in microscope transmission measurements

## 3. FSA FILTER ALIGNMENT

The FSA integration inside the detector holder was performed by Selex ES under supervision of TAS-I. The concept was to position the FSA inside the holder of the detector and after gluing it the holder is optically aligned with the sensitive area of the detector. Fig. 5 shows the Cassis filter layers sequence as it is the flight the detector from the telescope side (AR coating, black mask, fused silica substrate, LRC Black Mask, 4 passband coatings) and Fig. 6 shows the filter integrated inside on the Focal Plane Assembly (FPA) under UV light inspection (to check the dust contamination level due to the glue removal of the FPA cover) before to integrate it in the CaSSIS telescope [4].The filter sequence visible on the left of the picture is PAN, reflecting blue light and the filter on the right is BLU reflecting red and orange color.

Figure 5 CaSSIS filter layers sequence as it is the flight the detector from the telescope side (AR coating, black mask, fused silica layer, Black Mask, 4 passband coatings

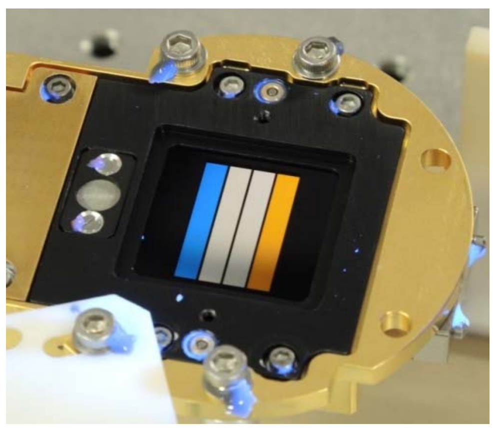

Figure 6. Picture of the filter assembly 10_5 integrated on the Focal Plane Assembly (FPA). The FPA was illuminated by UV light to check for contamination by dust. The filter on the left of the picture is PAN, reflecting blue light and the filter on the right is BLU reflecting red and orange light. In between, the RED and NIR filters both reflect all visible light and appear like mirrors

### 3.1 Alignment performances measurements

The alignment of a filter with respect to the active area of the detector has been measured by SES in collimated beam optical setup using halogen lamp. The USAF marker is used in the focus of the collimator and the refocused image obtained on the detector is acquired. Tab. 4 reports the obtained data.

Table 4 Data of alignment are obtained from the measurements

| Alignment data | Nominal value (mm) | Measured value (mm) |
|---|---|---|
| Filter-Detector Air gap | 1.343 ± 0.356 | 1.278 (Symbiosys filter) |
| Detector distance | 5.742 ± 0.254 | 5.626 |
| Detector parallelism | 0.0762 | 0.0371 |
| Detector Optical Area to Align - position | 0.127 | 0.08 |

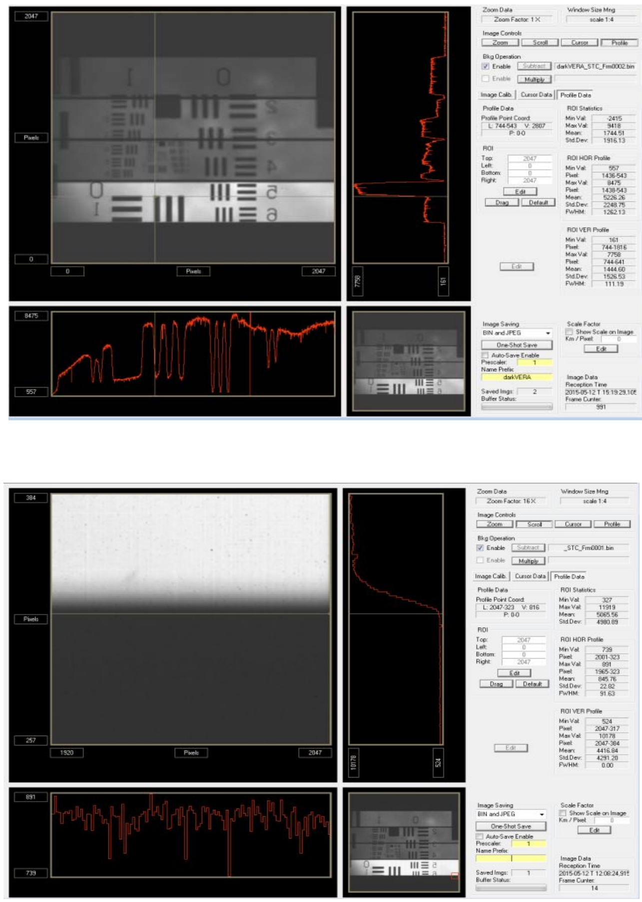

Figure 7 The USAF marker image (in the top) on the FPA sensitive area is used to measure the parallelism of the filter alignment edge vs the detector row direction–corner bottom left and right respectively (bottom piture).

The FSA with the dark inter-filter masks appears to be rather effective with cross-talk only detectable in 8 pixel rows nearest the inter-filter mask.

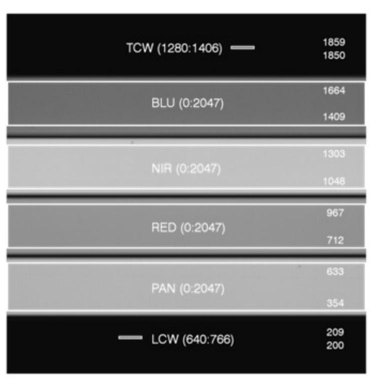


Figure 8 The 6 defined windows for the FPA (4 filters and the 2 in black masked area).

The FSA with the dark inter-filter masks appears to be rather effective with cross-talk only detectable in 8 pixel rows nearest the inter-filter mask. The exact positions of the framelets to be returned in nominal operation can be seen in relation to the full detector in Fig.8. The limited cross-talk has allowed us to propose a 2048 x 280 framelet for the PAN which increases the overlap between framelets by 9% thereby improving co-registration for the channel used mostly for stereo.

## 4. CONCLUSIONS

A new technique based on photolithographic processes of thin-film optical pass band coatings on a monolithic substrate has been applied to the filters of the Focal Plane Assembly (FPA) of the Colour and Stereo Surface Imaging System (CaSSIS) onboard of the ExoMars Trace Gas Orbiter launched in March 2016 by ESA.
Measured transmission curves through the centre of each of the bandpass filters of PFM CaSSIS filter performed by Balzers Optics Jena show PFM filter in space qualified and the four filters transmission are compliant with the requirement. The Field of View (FOV) of each colour band on the detector is surrounded by a mask of low reflective chromium (LRC), which also provides with the straylight suppression required (an out-of-band transmission of less than $10^{-5}$/nm). The mask has been shown to deal effectively with cross-talk from multiple reflections between the detector surface and the filter. This paper reports the manufactured process and optical properties of the FSA filters and the FPA preliminary alignment and on-ground calibration.

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