DEVELOPMENT OF A REAL TIME PARTICLE FALL OUT (PFO) MONITORING INSTRUMENT FOR SPACE LAUNCH APPLICATIONS

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Abstract. Launch vehicles, and their enclosed satellite payloads, experience significant degrees of mechanical and acoustic shock and vibration during their short journey into space. Nothing is currently known about the sources and types of particulate contamination inside a rocket fairing during launch, nor about the effect of reusability in cleanliness level evolution; however, it is certain that contamination can seriously affect the performance, accuracy and reliability of the multi-million dollar instruments which are routinely sent into space to study our planet and explore the universe. This paper describes the development of a unique instrument by XCAM Ltd, under contract to the European Space Agency (ESA), which will be launched on a Vega-C launch vehicle around 2024, to provide the first measurements of contamination during launch inside a rocket fairing.

1 INTRODUCTION

Effective contamination control is essential for the success of most space programmes because the presence of contamination can have severe detrimental impacts on the performances of spacecraft systems and subsystems, and could lead to partial or total loss of the mission and scientific objectives. Particulate contamination can cause a number of issues related to surface obscuration, absorption and emittance changes, light scattering, noise on electrical contacts, short circuits and mechanical damage to optical surfaces. The current practices aim to control the environments in which the spacecraft (sub)systems reside, which are usually cleanliness-controlled areas and clean rooms. For particles below 5 microns in size airborne monitoring is commonly performed but particles greater than 5 microns in size typically fall out onto surfaces and so airborne monitoring is often complimented by particle fallout (PFO) monitoring.

Different techniques exist, but unfortunately, none of the methods which are commonly employed (such as PFO counters, microscopic analysis of witness samples, tape-lifts from surfaces and particle counting of flushed eluents) are real-time measurements, and are therefore all retrospective in analysis and resulting corrective actions. In particular, there are a number of situations which are specific to spaceflight, such as inside the launcher fairing before, during, and right after launch, where particle fallout is difficult if not impossible to measure, as one cannot always easily access the surfaces to sample or retrieve the witness samples to measure.

In a previous paper (Holland, et al., 2016) we presented a novel technique for PFO monitoring which uses direct detection on a pixelated silicon image sensor by analysing the obscuration formed when a dust particle falls directly onto the surface of a semiconductor imager which is in an illuminated environment. This resulted in the development of a prototype PFO monitor, funded under contract to the European Space Agency (ESA) (Figure 1). This prototype successfully demonstrated the proof of principle in using this direct detection technique for real-time PFO monitoring down to 2.5 micron-sized particles.

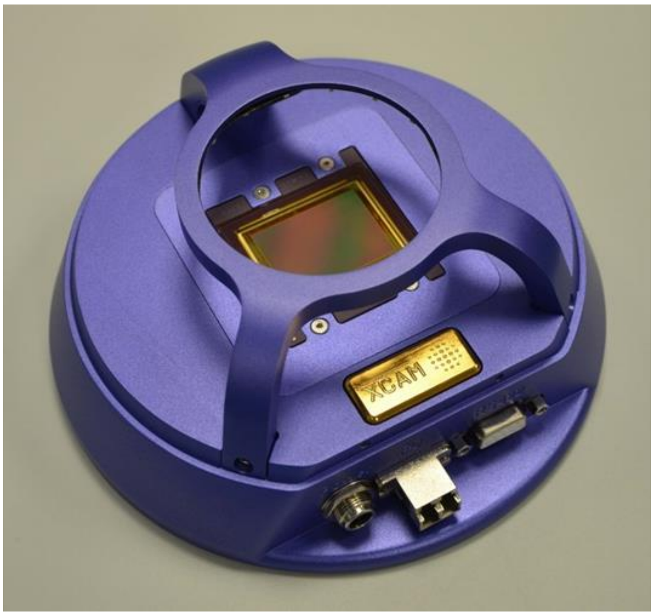

Figure 1: Image of the prototype PFO monitor developed under contract for ESA utilising a single imaging sensor and incorporating an illumination ring to illuminate the sensor in a dark environment

In a follow-up paper (Holland, et al., 2018) we describe an evolution of the prototype system for use in terrestrial-based applications, for example in cleanroom environments (Figure 2). Dubbed the PFO1040, the updated design of this PFO monitor replaces the single image sensor with four smaller sensors and retains the illumination ring to illuminate the sensors in dark environments. The PFO1040 also incorporates a software suite which analyses the raw images captured by the sensors, classifies and counts the particles and fibres present and reports percentage area covered (PAC) and PFO level as defined by ISO (14644-9:2012, 2012), IEST (IEST-STD-CC1246E, 2013) and ECSS (ECSS-Q-ST-70-50C, 2011) standards.

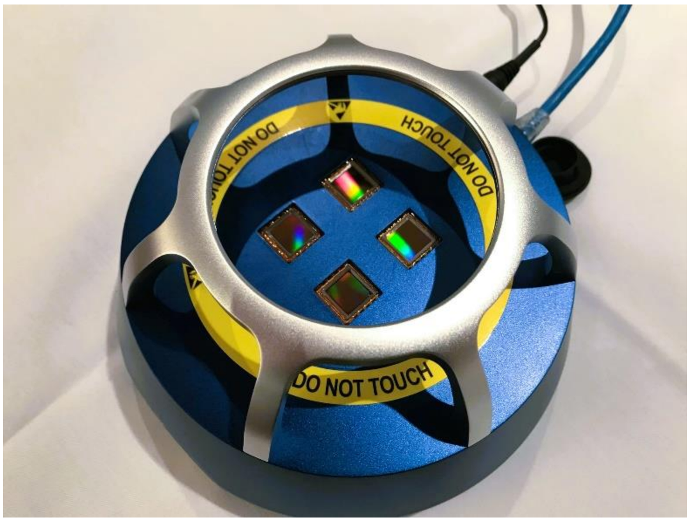

Figure 2: Image of the PFO1040 monitor developed for terrestrial applications utilising four imaging sensors and incorporating an illumination ring

The successful development of the prototype PFO and PFO1040 particle fall out monitors has led to the development of a space-flight qualified PFO monitor, under contract to the European Space Agency, which is the topic of this paper.

2 DESIGN

The development of instrumentation capable of operating during launch and in the space environment places unique challenges on spaceflight design engineers. Significant changes in temperature, pressure, humidity, vibration and shock need to be accounted for as well as incorporating the operational performance requirements of the instrument itself, materials and outgassing requirements and the launcher interface requirements in a highly reliable package.

2.1 Purpose and Concept of Operations (CONOPS)

The primary purpose of the space PFO monitor is to detect particles and fibers within a launch vehicle (LV) fairing during launch and subsequently provide the first measurements of surface contamination within that environment. In meeting this purpose the space PFO monitor is not envisaged to be the primary payload on the LV (i.e. taking these measurements will not be the primary purpose of the launch) and will share the LV fairing with one or multiple other payloads due to be placed into orbit. The design and concept of operations (CONOPS) of the space PFO monitor therefore takes an approach that minimises the interface and communication complexity with the LV reducing operational risk to the LV and primary payload(s) and development costs.

Importantly there will be no communication between the LV and the space PFO monitor. The space PFO monitor will operate autonomously when power is applied and by following a single pre-defined scheduler which will take inputs only from internal diagnostic data and measurements made by auxiliary sensors. This means that data collection will commence at power-up and that data delivery to the LV data acquisition system will also commence at power-up. This enables the PFO to be monitored when power is first supplied to the unit during launch vehicle integration and prior to and during transfer of the LV to the launchpad.

During launch, the space PFO monitor will need to independently detect the launch as it occurs, in order to move into its 'flight' mode of operation. A pre-scheduled sequence (the scheduler) will be programmed into the unit, giving commands at each point during the flight. The baseline is that the unit will commence taking images at power-up, and then after launch is detected it will take an image every 10 seconds up to and just after fairing ejection at 254s. During this time, the unit will also be compressing images and ordering them, for delivery to the LV data acquisition system for downlink to the ground. Transfer to the data telemetry system may occur for a much longer duration after data collection has been completed (4-5 hrs.).

2.2 Design Requirements

The list of design requirements for the space PFO monitor is considerable. Table 1 provides a top-level summary of the requirements for the instrument.

Parameter	Requirement
Detection Area	5 cm^2
PFO	ability to detect and classify particles and fibres and measure PAC and PFO level based on particle size distribution
Minimum particle size	5 micron
Sampling frequency	At least every 10 s
Instrument Volume	< 2 litres
Instrument Mass	< 2 kg
Electrical Interface	28V power, RS422 data
Maximum power consumption	75W on a supply of 28V
Operational temp. range	-20ºC to +80ºC
Operational humidity range	0% to 95%
Operational lifetime	data acquisition (at least 254s) data transfer (at least 5 hrs)
Shock and vibration	as per Vega C requirements
Placement	able to operate both horizontally and vertically

Table 1: Top-level requirements for the space PFO monitor

The requirements specified in Table 1 are defined by the customer, ESA, for a target launch vehicle, the Arianespace Vega C. The Vega C is a vertical launch two-stage to orbit vehicle capable of launching up to 3,300 kg to low Earth orbit (LEO) from the Arianespace Spaceport in French Guiana.

As well as the top-level customer requirements, and the requirements specified by the launch vehicle operator, XCAM are incorporating further requirements into the design to enable the unit to be launcher agnostic and operate from any launch site around the world.

2.3 Space PFO monitor design

The current design of the space PFO monitor is shown in Figure 3. This is the design for the engineering model (EM) (which undergoes substantial testing) but it is likely that the final design for the flight model (FM) may be different having learned lessons on the design from the EM.

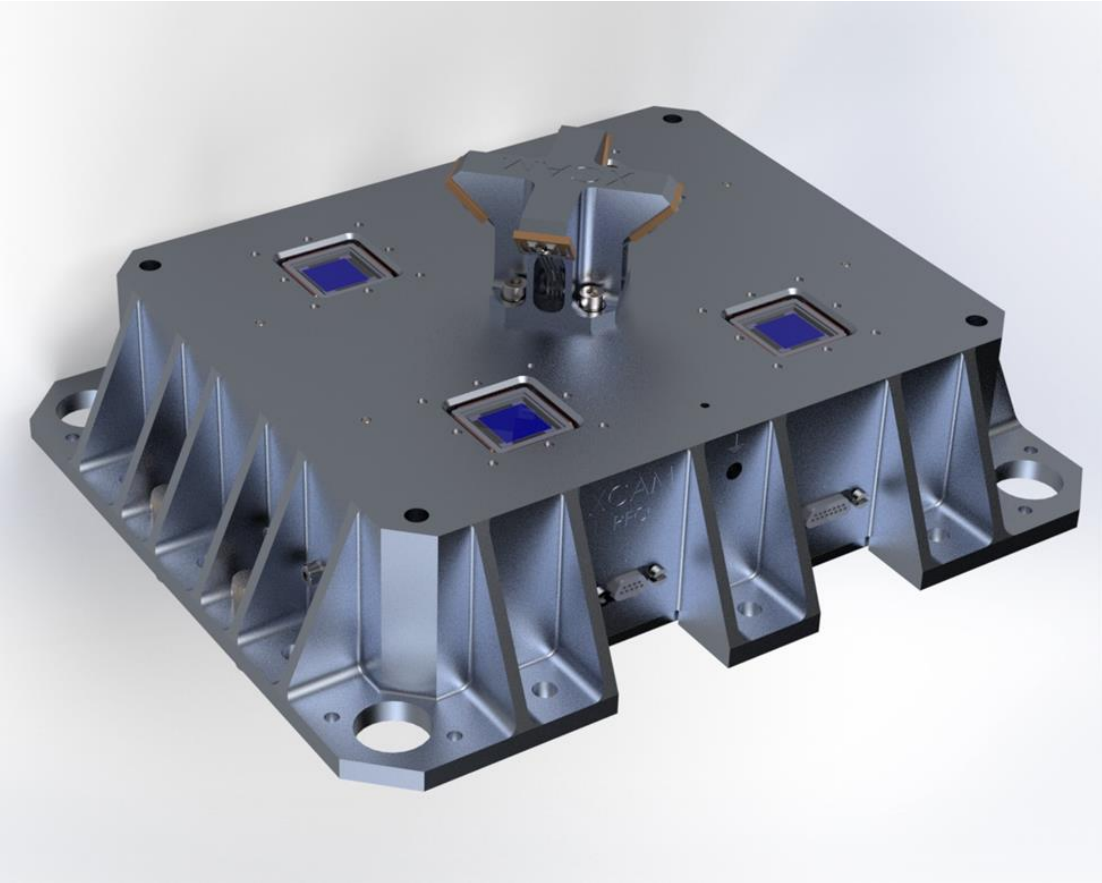

Figure 3: XCAM space PFO monitor design (engineering model)

The space PFO monitor primarily consists of a 198 x 166 x 45 mm^3 body and a 30 mm high central illumination post. The body houses four 14 x 14 mm^2 image sensors identical to those used in the PFO1040 (Holland, et al., 2018). The vented aluminium body design is ruggedised to withstand the launch vibration and shock environment and incorporates standardised mounting points for shock absorbers commonly used for space launch enabling it to withstand the significant variation in launch environments present across different launch vehicle families. The illumination post contains four light emitting diodes (LEDs), one for each sensor, enabling illumination of particles and fibres with the dark closed fairing environment. Internal to the body are the electronics sub-systems enabling management of the sensors, power and data interfaces, the thermal control sub-system and the harnesses and connectors. Finite Element Analysis (FEA) and thermal modelling has been carried out confirming that the instrument design is compliant with the thermal and mechanical vibration and shock loads specified in the requirements.

2.4 Key Design Trade-offs

Key design trade-offs were made as a result of the work undertaking in developing both the prototype PFO monitor (Holland, et al., 2016) and the cleanroom PFO1040 versions (Holland, et al., 2018).

Detector selection was one of the most important aspects of the work and a large number of detector technologies was reviewed against a detailed list of requirements in order to arrive at a suitable detector type. Extensive trials were conducted on various detectors over a period of time to practically evaluate their suitability for this use.

Illuminating the sensors is an important part of the measurement technique and both the prototype and PFO1040 version adopted an LED illumination ring structure to achieve this. Implementing the same for the space PFO monitor, that would need to resist launch loads, resulted in a more massive structure that would have led to the detectors being more obscured from falling particles, which was deemed unacceptable. Further iterations resulted in the current design incorporating a centralised illumination post with the four sensors moved further to the outer parts of the body (compared to the PFO1040). This configuration enables detector illumination with the added bonus of providing a central mechanical support structure adding further rigidity to the main body of the unit.

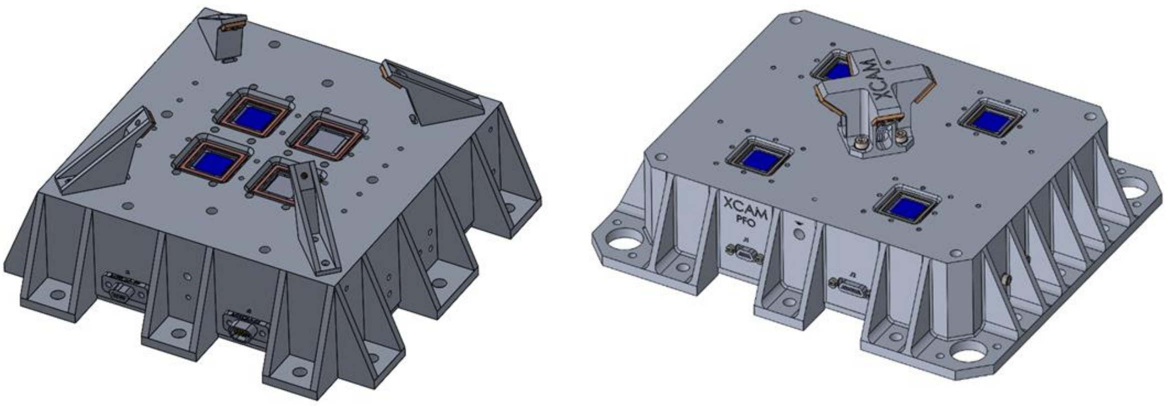

Figure 4: Illumination design concepts following incompatibility of the ring structure. Earlier iteration (left) and final iteration (right)

As space is a vacuum environment it is important to design using materials with as low outgassing properties as possible (the requirements for this instrument are to use materials with a Recovered Mass Loss (RML) ≤ 1.0% and a Collected Volatile Condensable Material (CVCM) ≤ 0.1% as per (ECSS-Q-ST-70-02C, 2008). Outgassing can be reduced further by using a hermetically sealed unit (to contain outgassing within the unit). Typically, hermetically sealed units increase mass due to the requirements for hermetically sealed feedthroughs and their mating connectors and the need for more fasteners. In addition, the Vega C launch vehicle requirements specify that all connector interfaces must be of male gender thus requiring the use of larger sub-D connectors (rather than micro-D) or having custom connectors made. Finally, hermetically sealed units incur greater manufacturing and testing time and costs. Overall therefore the conclusion was that a hermetically sealed unit would not be a cost-effective solution to minimise the effects outgassing. The alternative solution chosen was to adopt a vented design for the unit and choosing materials and processes that minimise outgassing as much as possible. One key requirement of a successfully vented design is that venting must be controlled in a direction away from the payload, or that the collection of the volatile materials is controlled, so that there is no danger of contaminating critical surfaces. Figure 5 shows the design approach taken which also complies with the electromagnetic compatibility (EMC) requirements for the unit.

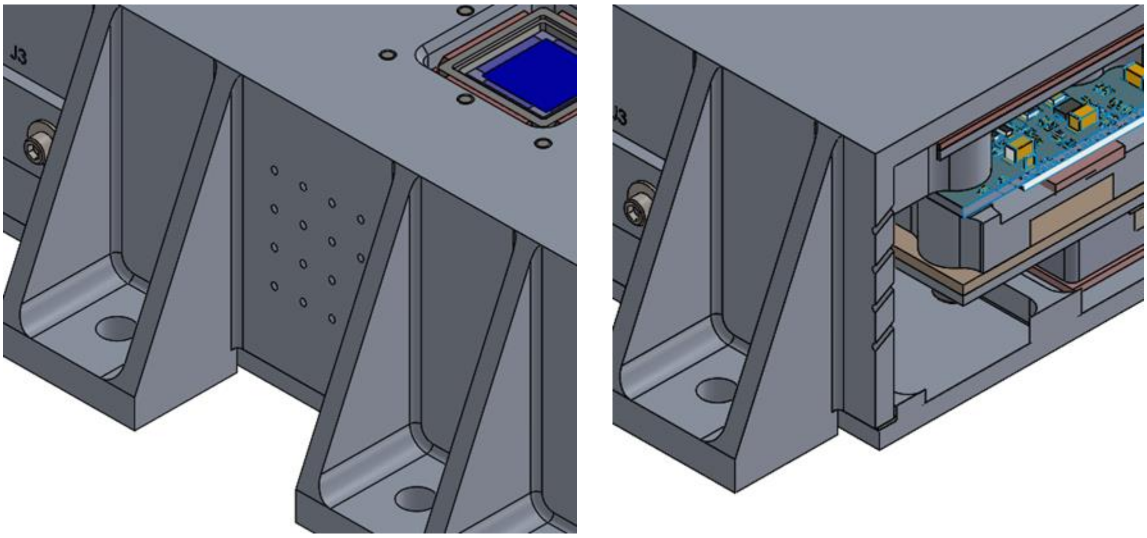

Figure 5: Vented design implemented to reduce the risk of contamination due to outgassing (left) and cross-section (right)

As the space PFO monitor is designed to monitor surface contamination it is vital that the critical sensing surfaces are protected at all times up to the point of launch. However, as highlighted in 2.1, there is a requirement to measure particle fall-out during the period between the unit being assembled into the LV and launch itself. As the levels of particle fall-out in this environment are unknown it is important to minimise the risk of sensor saturation in this pre-flight mode, which, if it occurred, would render the flight pointless. To this end, a two-part remove-before-flight cover (Figure 6 – left) was designed which only exposes one of the four sensors to the pre-flight environment once the unit is assembled into the LV (Figure 6 – middle). When the LV is delivered to the launchpad, the remaining part of the remove-before-flight cover can be removed exposing the remaining three sensors for the duration of the mission (Figure 6 – right). With this two-part remove-before-flight cover the critical surfaces can be protected during shipping and storage and PFO measurements taken both during the pre-flight and the flight periods of the launch.

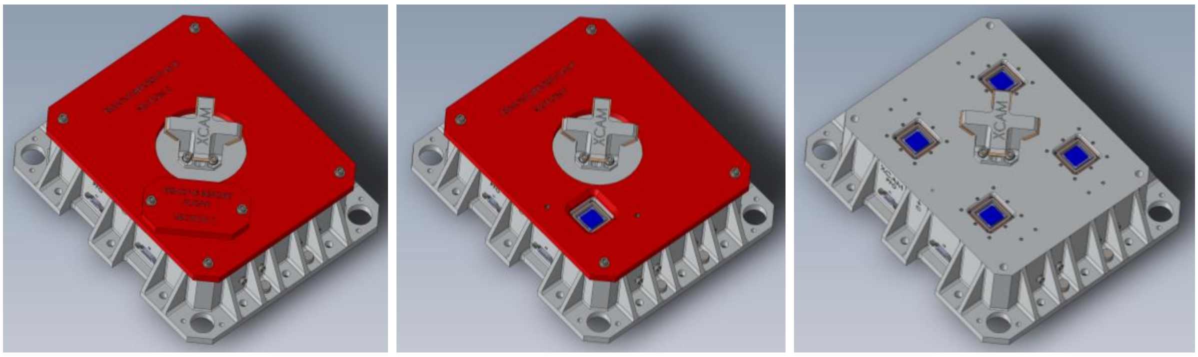

Figure 6 Pre-flight protection for critical surfaces: shipping configuration (left), pre-flight configuration (middle) and flight configuration (right)

Many other trade-offs and design decisions have been made to ensure space-flight compatibility and affordability of the space PFO monitor including surface finish of the housing, designing for high reliability vs. affordability, fully and partially redundant electronics design, communications protocols, launch detection systems and on-board data analysis software.

3 SPACE PFO MONITOR ENGINEERING MODEL TEST CAMPAIGN

At the time of writing XCAM have designed and built the engineering model (EM) of the space PFO instrument (Figure 7).

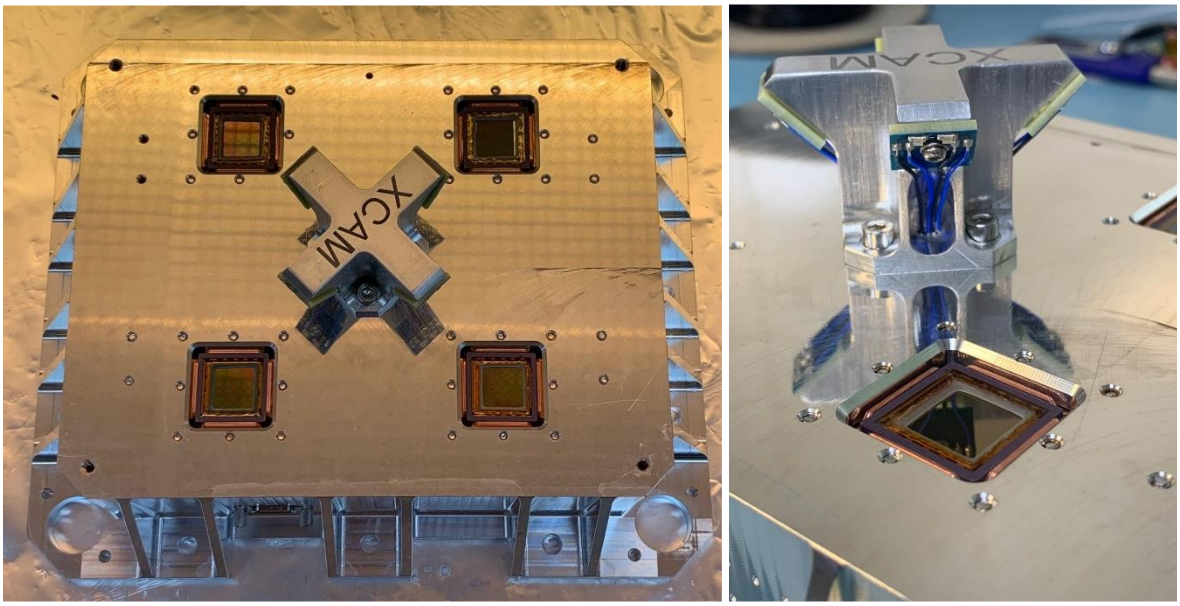

Figure 7 : Engineering model (EM) of the space PFO monitor (left) and (right) close-up of the illumination post and one of the silicon CMOS sensors

The EM shares the same form, fit and function as the envisaged final design except that the materials and components used are, for the most part, of lesser quality than the ‘space grade’ parts typically used for spaceflight instruments. The purpose of the EM is to demonstrate (through testing) that the concept of the final design is sound and that the instrument functionality and performance requirements can be met.

The EM unit test campaign is extensive and will demonstrate the unit's performance across a number of areas including;

- Functional requirements (e.g. performance characteristics, image sensor characteristics, control functionality, processing functionality, image storage capability, illumination capability, data transfer functionality, diagnostics and monitoring capabilities)
- Mission requirements
- Interface requirements (e.g. mechanical, thermal, electrical and harness interfacing)
- Environmental requirements (e.g. temperature, pressure and humidity, mechanical, electromagnetic, radiation)
- Operational requirements
- Logistics and support requirements
- Physical requirements (e.g. mass, volume, materials, cleanliness)

Delivering the test campaign will involve the use of many test facilities both internal to XCAM in the UK and at the European Space Technology Centre (ESTEC) in the Netherlands including environmental test chambers, vacuum test chambers and electromagnetic compatibility (EMC) test facilities.

Central to the instrument performance elements of the campaign is an ability to demonstrate the space PFO monitor detecting particles and fibres down to 5 microns in size. This is achieved by placing a specially designed and calibrated chrome-on-glass test mask onto the sensors (Figure 8 – left). The chrome-on-glass test mask has well-defined particle and fibre size combinations including 'particles' (3.5, 10, 20, 40, 75 and 150 microns), straight 'fibres' (5 and 10 microns) and curly 'fibres' (5 and 10 microns). Given the design similarities of the space PFO monitor and the cleanroom PFO1040 version, the XCAM PFO analysis and classification algorithms will be able to identify the 'particles' and 'fibres' of the test mask as shown in Figure 8 – right.

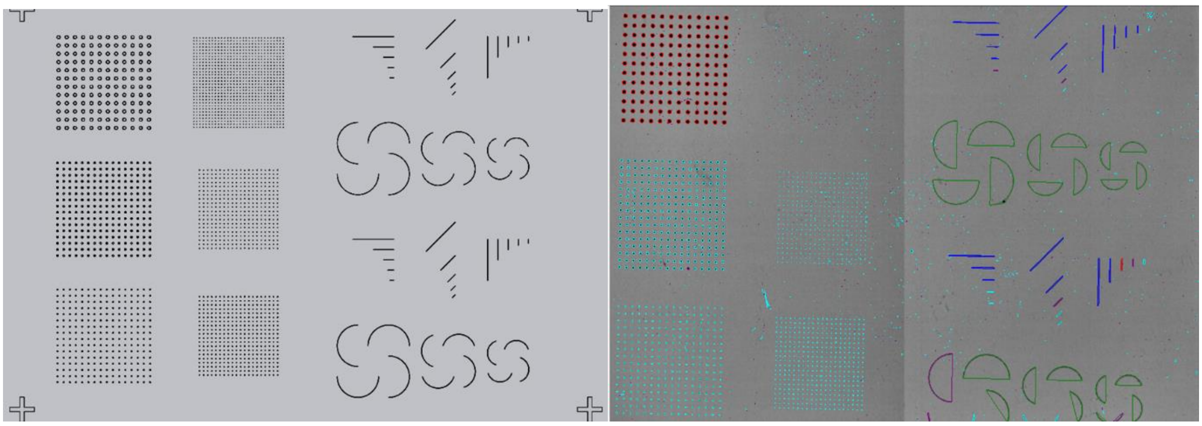

Figure 8: Chrome-on-glass test pattern (left) showing particulates of different sizes, straight 'fibres' and curly 'fibres' and (right) output from the PFO reporting suite showing an image from the PFO with particulates classified by the software by type (red = 'large' particles, cyan = 'small' particles, green = curly fibres, blue = straight fibres)

4 CONCLUSIONS

Effective contamination control is essential for the success of most space programmes because the presence of contamination can have severe detrimental impacts on the performances of spacecraft systems and subsystems, and could lead to partial or total loss of the mission and scientific objectives. There are a number of situations to spaceflight, such as inside the launcher fairing before, during, and right after launch, where particle fallout is difficult if not impossible to measure, as one cannot always easily access the surfaces to sample or retrieve the witness samples to measure.

In this paper we have described the development and test plan of a unique instrument being developed by XCAM Ltd, under contract to the European Space Agency (ESA), which will be launched on a Vega-C launch vehicle around 2024, to provide the first measurements of contamination during launch inside a rocket fairing.

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