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The ASIM Mission – A Contamination Control and Thermal Approach

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I. Abstract

The Atmosphere-Space Interactions Monitor (ASIM) is a European Space Agency (ESA) payload developed by the ASIM industrial consortium with Terma A/S, Denmark, as prime contractor. ASIM is mounted on the exterior of the European Columbus laboratory module on the International Space Station. Launched in April 2018 on the Space-X CRS-14 this external payload is a collection of optical cameras, photometers and an X- and gamma-ray detector designed to look for electrical discharges born in stormy weather conditions that extend above thunderstorms into the upper atmosphere.

Now almost three years into nominal operations, ASIM is continuously collecting data which researchers utilise for investigation of the relationship between terrestrial gamma-ray bursts, lightning and high-altitude electric discharges across all seasons, different latitudes and different times of day and night. As part of this successful operation many new design concepts, materials choices and processes had to be implemented for ASIM in order to mitigate against phenomena such as cross contamination, in orbit debris and plume due to the sensitive nature of optical sensors and radiator surfaces. There is also the need to comply with non-scientific ISS external contamination and deposition requirements during the intended operational phase.

As part of this design and development overview, this paper will give an overview of the ASIM mission, a brief description of the instruments and focus on the cleanliness and contamination approach , implementation of bake-out and outgassing strategies and preconditioning, contamination budgets and cleanliness mitigations during AIT as well as the use of cleanliness mitigation concepts in the design, such as decontamination heaters on sensitive optics, venting design and dust caps to protect sensitive surfaces. Also external ISS outgassing requirements must also be met. In addition, an overview of the ASIM thermal design control will be presented and to consolidate and substantiate the cleanliness approach, real in-orbit data and science feedback from the mission are presented showing how contamination has affected or not its performance. In conclusion an overview based upon the cleanliness and contamination will be shown based upon the mission.

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II. ASIM – Science overview and objectives

Launched on April 2, 2018, ASIM carries dedicated instruments designed to measure Transient Luminous Events (TLEs) and Terrestrial Gamma-ray Flashes (TGFs), generated by the electrical activity of thunderstorms. TLE is the common name for glimpses of light in the stratosphere and mesosphere above thunderstorms. They include electrical discharges such as sprites, jets and gigantic jets, and luminous excitation of the atmosphere such as the elves. TGFs are bursts of bremsstrahlung from energetic particle beams accelerated in thunderstorm processes. These photons reach energies that allow for pair production of positrons and electrons. Transient Luminous Emissions (TLEs) are electrical discharges that include blue glimpses at the top of thunderstorms, blue jets, gigantic jets and red sprites. TLEs also include elves, the rapidly expanding rings of emissions at the bottom ionosphere, and the halos. [10]. A pictorial representation of the main entities are shown in Figure 1 below.

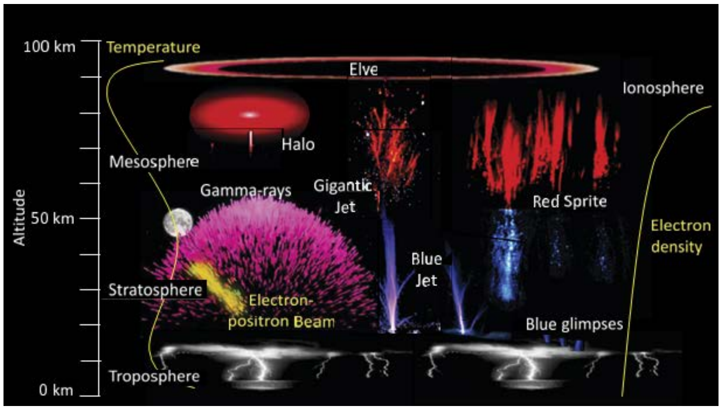


Figure 1 Pictorial representation of the upper atmospheric phenomena powered by thunderstorms. Credit DTU Space; TGF: NASA[10]

The primary science objectives of the ASIM mission include:

- Provide a comprehensive survey of the occurrences of Transient Luminous Events (TLEs) and Terrestrial γ -flashes (TGFs) on a global scale;
- Study the physics of TGFs and their relationship with TLEs and lightning;
- Study the physics of TLEs;
- Determine the characteristics that make thunderstorms TLE- and TGF-active;
- Study the coupling to the ionosphere of thunderstorms and TLEs;
- Study the effects of thunderstorms and TGFs on the Earth’s radiation belts.

III. ASIM payload- A technical overview

The ASIM payload with its instruments is shown in Figure 2. The Modular X-ray and γ-ray Sensor (MXGS) and the Modular Multi-spectral Imaging Array (MMIA) are mounted on the Columbus External Payload Adapter (CEPA) together with the main Data Handling and Power Unit (DHPU), and the MMIA instrument Data Processing Unit (MMIA DPU). The MXGS DPU is a derivative of the MMIA DPU and is mounted internally MXGS together with the MXGS power supply. The MMIA DPU provides power conditioning for the MMIA sensors.

The CEPA provides the structural platform for the payload as well as power and data connections between ASIM avionics and the ISS (see Figure 4). The DHPU converts the 120V power supply from the ISS to 28V instrument supply and handles all data communication. The ASIM total mass is 314 kg and its dimensions are 122×134×99 cm^3.

The main industrial contractor was Terma A/S, Denmark. Terma A/S was also the main subcontractor of the MMIA together with the Danish Technical University (DTU). DTU was main subcontractor for the MXGS in cooperation with University of Bergen, University of Valencia, and Space Research Centre, Polish Academy of Science. OHB Italy was main subcontractor for the DHPU as well as ASIM level AIT and ISS safety certification. The ASIM comprises the following subsystems: A NADIR-looking instrument assembly, housing the Modular Multi-spectral Imaging Array (MMIA) and the Modular X-ray and γ -ray Sensor (MXGS) instrument, as well as some support structures and radiators.

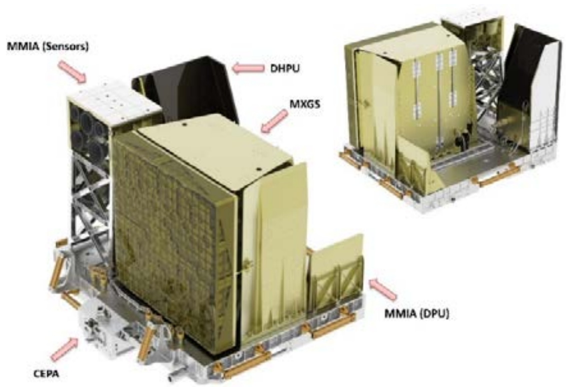


Figure 2 ASIM Payload showing instrumentation overview

The Modular X- and Gamma-ray Sensor (MXGS)

The main objectives of MXGS are to image and measure the spectrum of X- rays and γ -rays from lightning discharges, known as Terrestrial Gamma-ray Flashes (TGFs) [11]. With an imaging system and a large detector area MXGS will, for the first time, allow estimation of the location of the source region and characterization of the energy spectrum of individual events. The sensors have fast readout electronics to minimize pileup effects, giving high time resolution of photon detection for comparison with measurements on µs-time scales of lightning processes measured by the MMIA and other sensors in space or on the ground. The high (HED) and low (LED) energy detectors cover the large energy range of the relevant photon energies as shown in Table **1** [10]

Table 1 MXGS overview showing detector parameters and ranges

MXGS	LED	HED
Geometrical area (cm^2)	1024	900
Energy range	15–400 keV	200 keV–20 MeV
Energy resolution	$<$ 10% @ 60 keV	$<$ 15% @ 662 keV
Angular resolution point source	$<$ 0.7°	
Relative time accuracy	10 µs	10 µs
Sensitivity (signal/noise)	$>$ 7	$>$ 15

The Modular Multispectral Imaging Array (MMIA)

The purpose of the Modular Multi-spectral Imaging Array (MMIA) instrument is to image the upper atmosphere in the near infrared and ultraviolet parts of the spectrum and to make simultaneous photometer readings. The MMIA instrument is looking towards Nadir, observing the same area as the MXGS instrument, in order to identify correlation between TGFs, detected by MXGS, and TLEs, detected by MMIA. The MMIA contains three Photometers (PHOTs) and two Camera Head Units (CHUs) mounted in the MMIA Sensor Unit (MMIA SU). See Figure 3.

The two MMIA cameras are designed for 337 nm (CHU1) and 777.4 nm (CHU2) wavelength, respectively, and thus both requiring different optic and baffle design. The housing is the same for both configurations. The three MMIA PHOTs are designed for 337 nm (PHOT1), 180-230 nm (PHOT2), and 777.4 nm (PHOT3) [9] . The 337 nm and 777.4 nm configuration share the same optics (excluding filter) and baffle design. The broad banded photometer (180-230 nm) does not include any optics, only a cut-off filter.

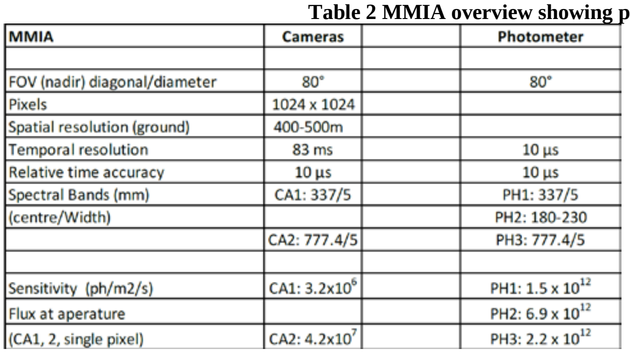
Figure 3 MMIA showing camera and photometer location and orientation

The PHOT's and CHU's feature a decontamination subsystem. For each PHOT and CHU a heater is capable of heating up the instrument front lens, and a thermistor is located close proximity to the lens. These heaters and thermistors are operated directly by the DHPU. The MMIA DPU is mounted directly onto the CEPA platform and placed behind the MMIA Support structure and MXGS instrument. The MMIA DPU is interconnected with the instruments on the optical bench dedicated MMIA harness.

The MMIA instrument performs science data acquisition during the night part of the ISS orbit. On the dayside, the DPU performs data processing and selection. During data collection, the DPU receives data from the two CHU´s and the three PHOT´s. The CHU´s are providing image frames to the DPU, while the PHOT´s are providing a photon count signal to the DPU.

Table 2 below shows the MMIA overview giving photometer and camera parameters and ranges. [9]

Table 2 MMIA overview showing photometer and camera parameters



MMIA	Cameras		Photometer
FOV (nadir) diagonal/diameter	80°		80°
Pixels	1024 x 1024		
Spatial resolution (ground)	400-500m		
Temporal resolution	83 ms		10 µs
Relative time accuracy	10 µs		10 µs
Spectral Bands (mm)	CA1: 337/5		PH1: 337/5
(centre/Width)			PH2: 180-230
	CA2: 777.4/5		PH3: 777.4/5
Sensitivity (ph/m2/s)	CA1: $3.2x10^6$		PH1: $1.5 x 10^{12}$
Flux at aperature			PH2: $6.9 x 10^{12}$
(CA1, 2, single pixel)	CA2: $4.2x10^7$		PH3: $2.2 x 10^{12}$

Figure 4 ASIM payload external attached to the ISS columbus CEPA platform

IV. ASIM –Thermal Control design and analysis overview

The different ASIM instruments and system equipment are accommodated together on a Columbus External Payload Adapter (CEPA). Each item on CEPA has (a) radiator(s) and other surfaces covered by MLI. The various MLI blankets have different inner layers, but in common that β-cloth (PTFE-coated fiberglass fabric) is used on the outside. The radiators are covered with Ag-PTFE tape. The Modular X- and Gamma-Ray Sensor (MXGS) is equipped with two Loop Heat Pipes and Axial Grooved Heat Pipes using propylene to move heat from instruments to the RAM radiator. Three Axial Grooved Het Pipes (AGHPs) spread the heat on the Zenith radiator. ASIM has three sets of heaters (thermostat-controlled); operational, survival and transport heaters.

The thermal analysis for the integrated ASIM assembly has been performed with the ASIM RTMM (ESATAN-TMS), consisting of a total of 350 diffusion nodes. For the Columbus worst-hot and worst-cold thermal environments, a worst-case search has been used to identify the combination of attitude (yaw, pitch and roll) and beta angle (sun elevation vis-á-vis the orbital plane) leading to the maximum and minimum temperatures per instrument (see **Figure 5**). The worst-case search is based upon thermal analysis using an interface thermal mathematical model (TMM) representing the ISS. The screening for the worst-case cold and hot conditions has been based on variation of Earth albedo between 0.2 and 0.4, Earth IR from 206 to 286 W/m^2, solar constant from 1321 to 1423 W/m^2 and altitude variation from 278 to 500 km.

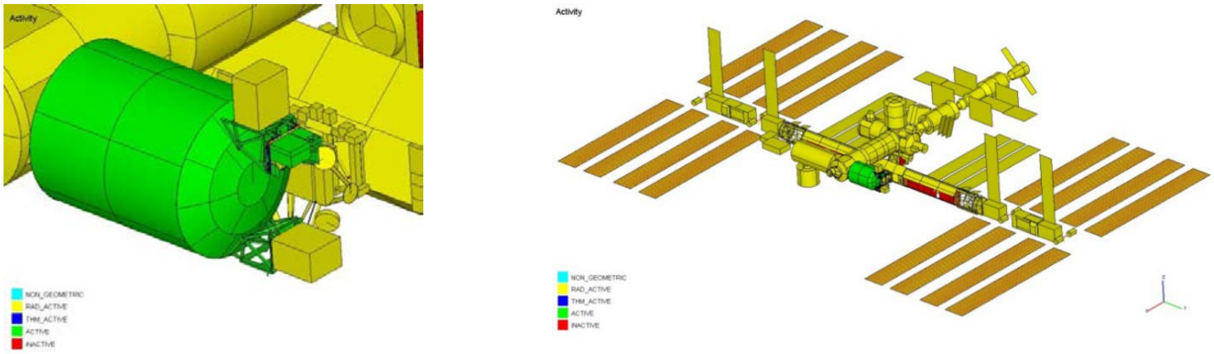


Figure 5 ASIM and Columbus thermal modelling

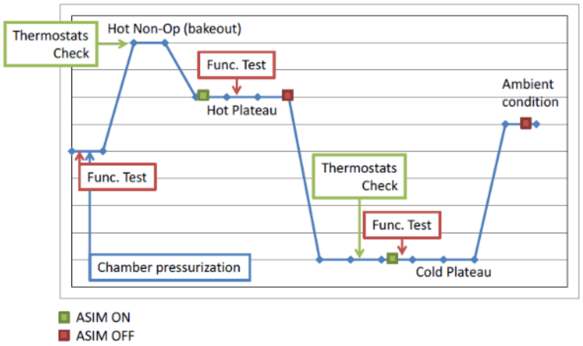
The ASIM power dissipation depends on the operational mode, notably on the night-time data collection state and the daytime data processing state, when it can vary between 180 and 270 W. ASIM is equipped with separate sets of heaters and thermostats for transport (for launch and transit to ISS) and on-orbit survival (non-operational cold conditions). The survival heaters are sized to generate up to 195 W at minimum voltage (111 VDC). For simplification of the thermal analysis per instrument, Terma has converted the corresponding conductors and heat exchange with the ISS into equivalent black body radiative sink temperatures, determined for each radiator separately depending on the orientation. Since the instruments and system equipment have radiators pointing in different directions and are largely thermally decoupled from each other, the worst-case sink temperatures represent different orbit conditions; beta angle and attitude parameters.

Thermal Control Verification

As part of the system level thermal qualification testing ASIM was subjected to a TVAC test at the IABG 2.5-m diameter chamber in Ottobrunn (D) in January 2017 (see Figure 6 and Table **3**) . During the test, it was accommodated on a Thermal Test Adapter, resting on rails inside the chamber. Thermal coupling between CEPA and the TTA was minimized by pads and MLI. Eighty-seven T/Cs were installed on ASIM and in the test chamber and in addition, data was acquired from internal temperature sensors[3]. Due to constraints in time and resources, and the position that established materials are used for the radiators and no detrimental solar trapping was known to occur, candidate facilities for the TVAC test were selected with no solar simulation.

In order not to need different shroud temperatures or IR heating around ASIM in the TVAC chamber, Terma performed thermal analysis to determine which of the items of ASIM would be the most critical for adjusting the test environment. As a starting point, the DHPU nominal environments were used for determining the equivalent test environment levels. The TSINK of the hot environment and the equivalent TSINK (set to compensate QS, QA and QE) were calculated. This equivalent sink temperature was then imposed on the other radiators, together with the relevant internal power dissipation values (different between on-orbit and test). Next the resulting instrument temperatures were compared to the design limits and the equivalent sink temperature was adjusted to the maximum value not resulting in negative margin for any temperature on the instruments. The same procedure was followed for the cold environment.

Figure 6(a) ASIM ready for TVAC at IABG[3]

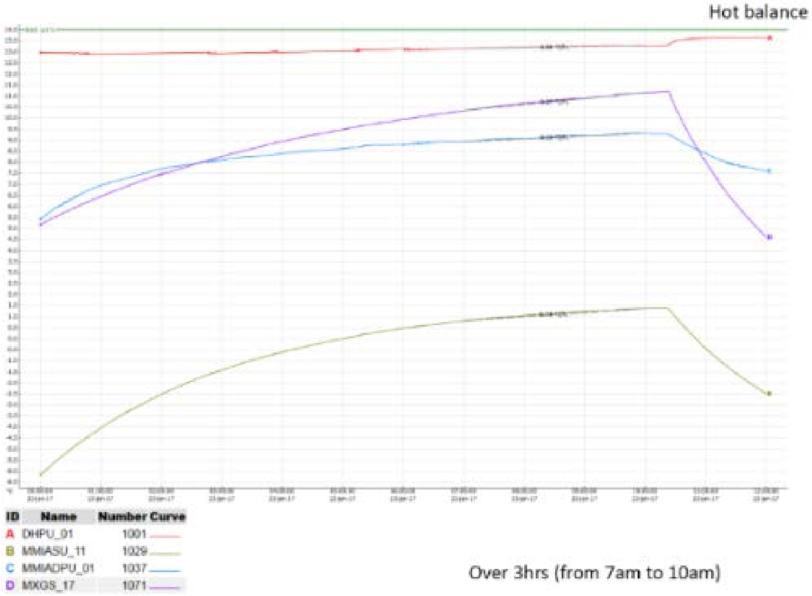


6(b) ASIM TVAC test profile[3]

The stabilization criteria for the hot and cold plateaus were set to a temperature change rate of less than 0.5°C/hours for two hours with at least 80 percent of the sensors (see Figure 7). While the procedure had allocated 48 hours for the thermal balance phases, stabilization was reached within 12 hours. [3]

Table 3 TVAC test sequence[3]

TVAC test sequence	
• 1 Thermal-vacuum chamber depressurization	• 2 Transient to hot case for thermostats verification (shroud @ +42°C): payload temperature raised to a temperature where all thermostats are supposed to be open
• 3 Transient to hot plateau environmental conditions (shroud @ -16°C)	• 4 ASIM activation and execution of the reduced functional test (good health check)
• 5 Payload configuration and temperatures stabilization for hot plateau	• 6 ASIM de-activation and transient to cold case for thermostats and heaters verification (shroud @ -35°C)
• 7 Heaters verification: Columbus and Transfer heaters	• 8 Heaters de-activation and transient to a safe switch-on temperature (shroud @ -10°C and DHPU > -15°C).
• 9 ASIM activation	• 10 Execution of the reduced functional test (good health check)
• 11 Payload configuration and temperatures stabilization for cold plateau (shroud @ -37°C)	• 12 Payload de-activation
• 13 Chamber and payload to ambient temperature, then re-pressurization	



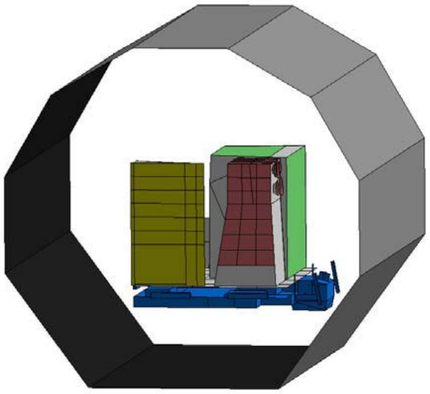
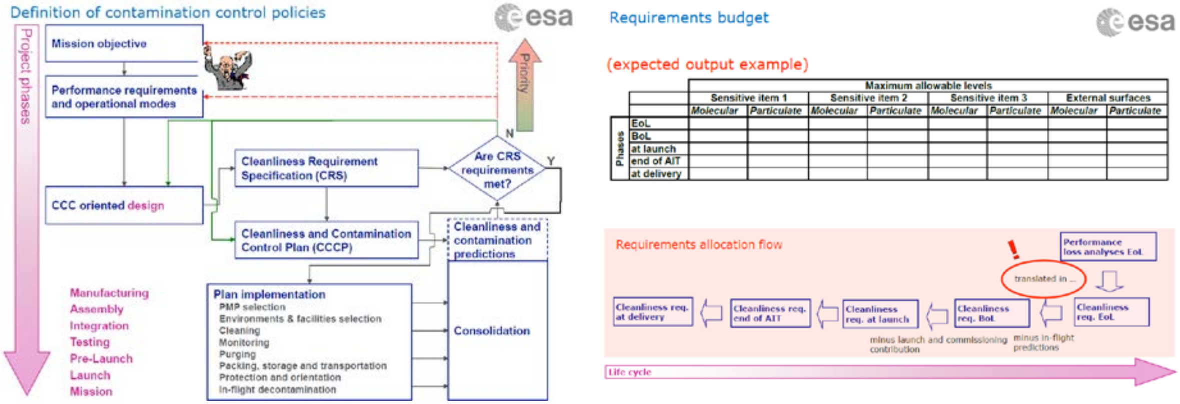


Figure 7 (a) ASIM TVAC hot plateau profile[3] **7(b) ASIM as modelled in the TVAC chamber[1]**

V. ASIM –Nominal Cleanliness and contamination control – environment

In order to comply to ISS external Columbus complement level analysis, contamination and cleanliness control was performed and carried out in order to assess contamination issues in relation to ASIM and the ISS. During all development, test and integration phases the ASIM unit's surfaces molecular and particulate contamination levels (MOC and PAC) was controlled in accordance with ASIM system level cleanliness requirements and in accordance with the ECSS-Q-ST-70-01. Figure 8 shows a generic cleanliness and contamination approach from mission objective and scientific parameters through to cleanliness level requirements, MAIT budget control, verification, and launch mission scenarios [8, 12]. For ASIM contamination control the scenarios were categorised into contamination scenarios including; 1) nominal contamination and control requirements (materials selection, MAIT, bake outs etc.) , 2) Pre-launch and contamination control (external payload and dragon contamination contributions) and 3) ISS contamination control requirements. A brief overview will be provided for these in the following section.



		Maximum allowable levels							
		Sensitive item 1		Sensitive item 2		Sensitive item 3		External surfaces	
		Molecular	*Particulate*	*Molecular*	*Particulate*	*Molecular*	*Particulate*	*Molecular*	*Particulate*
Phases	EoL								
	BoL								
	at launch								
	end of AIT								
	at delivery								

Figure 8 (a, b) Cleanliness and contamination and budget approach [12]

The ASIM contamination sensitive components have been identified as:
1) the MMIA where sensitive camera optics and photometers (principally the UV sensor-PHOT2) are present.
2) thermal hardware (radiators) have also been identified as contamination sensitive surfaces

In order to comply to subsystem and system requirements various levels of cleanliness control and mitigation (e.g. dust caps) have been implemented during the project phases and life cycle of the payload from materials selection and design, MAIT (MMIA camera optic assembly, focusing and test, MMIA photometer assembly and test, MXGS integration and testing), ASIM Payload assembly, integration and testing, pre-launch, launch and mission scenarios. In addition to the MMIA CHU and photometer front lenses Table 4 provides an overview of the ASIM contamination sensitive optics on ASIM:

Table 4 ASIM contamination sensitive surfaces

ASIM Unit	**Sensitive Items**	**Comments**
MGXS FM/PFM	None identified	No special handling requirements. ISO Level 8 sufficient
MMIA PFM	MMIA Camera Optics photometer	Optical devices must have dust caps fitted to their baffles during non-use and Kapton tape covering all venting holes. When covers and caps are removed the applicable maximum exposure times are as given in table 5b below
DHPU	None identified	No special handling requirements. ISO Level 8 sufficient

During all development, test and integration phases the ASIM unit's surfaces molecular and particulate contamination levels (MOC and PAC) were monitored and controlled in accordance with ECSS-Q-ST-70-01. In Table H-1 in [ECSS-Q-ST-70-01] cleanliness class 700 corresponds to an obscuration factor of 21469 mm^2/m^2 and this can be verified by using the visual clean (VCHS) method which transforms into the following maximum exposure time for a given ISO class as shown in Table 5a below. The contamination budget for activities with exposed sensitive items for the MMIA optics is shown in Table 5b below.

Table 5 a,b Contamination ISO classes and ASIM MAIT contamination budget

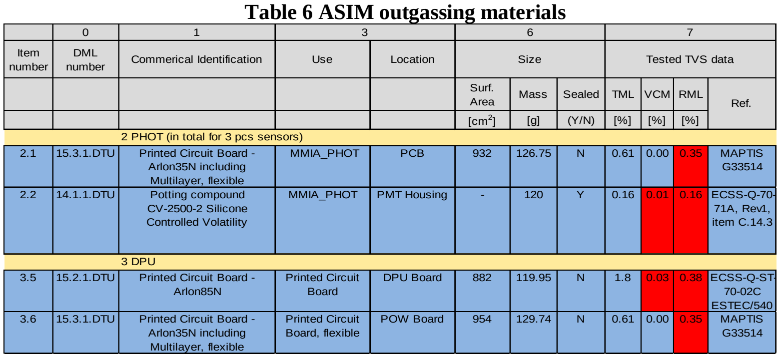
Clean Room ISO class	**Maximum exposure time in days**
5	10735
6	2147
7	413
8	78

Activity within Clean Room	Maximum exposure time in days of MMIA camera optics	Maximum exposure time in days of MMIA photometer
Manufacture	10	10
Assembly, focusing and test of sensitive item	5	5
ASIM assembly, integration and test	10	10
Launch site activities	43	43
Launch	10	10
Sum of activities in ISO class 8 (budget of 78 days)	78	78

For MAIT activities, once the ISO cleanroom maximum exposure time (maximum 78 days total in ISO 8) is not breached then for nominal operation under these conditions there is no contamination concern, which will influence the performance of the sensitive surfaces. Where the budget for the exposure time is expired, the optic front lens was cleaned to a VC cleanliness level. Here using ASAP stray light simulations it was shown not to indicate problems in the case where the front surface of the optics is at cleanliness level 700 and the rest of the surfaces are clean. The final ASIM assembly, integration and testing activities of the Flight Model was performed under class ISO8 conditions (optic assembly was performed in an optical flow bench in ISO5-class 100 conditions).

For transportation, assembly, and integration it was recommended that the instruments were thoroughly cleaned before packing/shipping and, again, before loading onto the launcher. Final packing, before shipment, was also performed under ISO Level 8 clean conditions. The contamination system level requirements were calculated and based upon a pre-launch and EOL PAC level of 21400ppm. For molecular contamination the EOL value was 1.3 $\mu g/cm^2$. The signal to noise ratios (SNR), on-ground particulate and molecular in-orbit calculations are provided in Table 10 below, here it can be seen that even sensitive surfaces have huge contamination margins for the MMIA camera optical and photometers (e.g. ground particulate of (2.15%) for CHU1 and 3% for 337 nm for molecular in –orbit lens attenuation).

Table 6 ASIM outgassing materials



	0	1	3		6			7			
Item number	DML number	Commerical Identification	Use	Location	Size			Tested TVS data			
					Surf. Area	Mass	Sealed	TML	VCM	RML	Ref.
					[cm^2]	[g]	(Y/N)	[%]	[%]	[%]	
		2 PHOT (in total for 3 pcs sensors)									
2.1	15.3.1.DTU	Printed Circuit Board - Arlon35N including Multilayer, flexible	MMIA_PHOT	PCB	932	126.75	N	0.61	0.00	0.35	MAPTIS G33514
2.2	14.1.1.DTU	Potting compound CV-2500-2 Silicone Controlled Volatility	MMIA_PHOT	PMT Housing	-	120	Y	0.16	0.01	0.16	ECSS-Q-70-71A, Rev1, item C.14.3
		3 DPU									
3.5	15.2.1.DTU	Printed Circuit Board - Arlon85N	Printed Circuit Board	DPU Board	882	119.95	N	1.8	0.03	0.38	ECSS-Q-ST-70-02C ESTEC/540
3.6	15.3.1.DTU	Printed Circuit Board - Arlon35N including Multilayer, flexible	Printed Circuit Board, flexible	POW Board	954	129.74	N	0.61	0.00	0.35	MAPTIS G33514

As an example of the materials selection and bake out, at materials and part level there were no materials considered outgassing critical for the ASIM self-contamination, which have not been baked. Baking was selected at line level when e.g., PCB manufacturing and assembly level, and when the outgassing parameters of a material were based on certain pre-conditioning. Table 6 above shows the deviating outgassing materials (TML-total mass loss, CVCM collected volatile condensable material, RML -recovered mass loss) and item level bake outs (e.g. Mapsil 213 on PCB boards).

Figure 9 Venting design for PHOT and PCBs showing venting of potting material through the electronics box or outwards through the front of the optics.

Figure 9 shows that even though CV-2500 is used in close proximity to the optics, the design and venting configuration justify use. Taking the MMIA Functional and Performance Analysis[4] the transmittance of 97% results in a performance SNR of 1975 for Elves (the performance for PHOT1 is specified for the Elves event). Even Considering 88% transmittance in the radiometric budget due to outgassing materials on the most sensitive camera, the resulting SNR is 1792 way above the requirement of 15 as per system level requirements.

Of the sensitive surfaces above, only the MMIA sensors front lenses are significantly sensitive to contamination. The MXGS is an X and gamma ray energy detector which requires high-density materials in order to absorb the incoming signal and the thermal radiators impact is taken into account in the worst-case conditions of thermal analysis. The area is depicted in Figure 10. The mask front layer will be contaminated during flight. A two-year mission will result in a contamination layer with a thickness of ~13µg/m^2 (end-of-life molecular level). However, the X-ray absorption for such a thin layer is insignificant in the LED energy band for any possible material composition and can therefore be ignored. For the same reason, the MMIA SE baffles have protective dust caps (shown in Figure 10a) to protect the front lens against particulate contamination during ground handling. The dust caps (black covers) are press-fit and were removed before flight items. The ASIM thermal radiators are shown in Figure 10b below[2]. The thermo-optical properties of the radiators are affected by the contamination environment. The end-of-life (EOL) properties were chosen with significant margin (see **Table 7**) to account for possible degradation of thermo-optical change due to contamination, hence thermo-optical performance degradation due to contamination was not a concern.

Table 7 BOL and EOL thermo-optical properties

Optical	BOL		EOL	
	ε_{IR}	α_{SOLAR}	ε_{IR}	α_{SOLAR}
CEPA Beta cloth 1)	0.8	0.2	0.815	0.5
MXGS Beta cloth foil 1)	0.8	0.2	0.815	0.5
MXGS Silverized Teflon tape 10mil 2)	0.84	0.093	0.84	0.14
MXGS Silverized Teflon tape 5mil 2)	0.78	0.066	0.78	0.10

Figure 10 a, b MMIA and thermal radiators[2]

VI. ASIM to ISS environment- Dragon Transportation

To confirm that no transportation or dragon contamination environment had an effect on ASIM, during discussions with NASA and Space-X, Terma provided an assessment of margin, which was considered for the Dragon transportation. This was considered as well as the decontamination heaters implemented on the front lens optics, in order to vaporize any molecular contaminants by heating the lenses.

The MMIA functional and performance analysis [4] , considers 5% attenuation of the optics. This was based upon a 2% attenuation loss for particulate coming from 78 days of ground exposure in class 100k (ISO 8) [7]. The remaining 3% loss was from the in-orbit environment as described in Figure 11 below. The 5% attenuation considered in the MMIA functional analysis report [4] still shows a SNR well above the requirements[6]. Considering the margin to the SNR requirements, an additional 165,000 mm^2/m^2 particulate or 75 mg/m^2 molecular deposition could still be allowable. It was shown that retaining a 50% margin, and splitting evenly the allocation between particulate and molecular, the following allowables would be considered for the Dragon transportation environment:

- particulate allocation 42500 mm^2/m^2 resulting in 4.25% further attenuation
- molecular allocation 18.75 mg/ m^2 resulting in further 3.78% attenuation.

Considering this allocation, the resulting SNR for the most critical sensor (CHU1) would only be reduced from 19 to 17, which is still above the minimum SNR requirement of 15 required by system level requirements. [6]

VII. ASIM to ISS environment- NASA/ ISS contamination assessment and compliance

The contamination analysis comprises contamination from ASIM towards and ISS/Columbus and vice-versa by ensuring that all materials and processes within ASIM declared materials are compliant with the ISS/Columbus requirements. An important part of the analysis is to assess the local contamination environment for the ASIM science instruments based on the ASIM design and the ISS contamination environment. This allows a performance assessment of the instrument performance over the lifetime of ASIM. For ISS contamination and environment the identification of possible ISS/Columbus contamination sources as well as an assessment for each identified source of the impact to the MMIA front aperture in terms of transmission attenuation, distortion, and stray light generation and an assessment for each identified source of the impact to the MXGS detector plane (kapton foil covered) is required.

When assessing the inputs provided by ASIM, it must be considered also that ASIM equipment has undergone several thermal vacuum tests prior to launch. All subsystems have undergone thermal cycling and thermal balance test in vacuum environments, in addition to thermal vacuum tests, the MXGS equipment and also the MXGS subsystem were subject to baking. Following sub-system testing, the ASIM Payload was subjected to thermal cycling and thermal vacuum testing. In addition to testing, ASIM has been transported to ISS in the Dragon trunk, which is exposed to space vacuum. The free flight to ISS is also several days. For these reasons, ASIM contribution to the ISS contamination environment will be greatly reduced[7].

For the ASIM payload Payload System Specification cleanliness requirements shall comply with the on-orbit external contamination environments[15] which state for quiescent periods that the molecular column density (MCD) shall not exceed $1x10^{14}$ molecular–cm–2 for individual released species and that molecular deposition rates shall not exceed $1x10^{-14}$ $g–cm^{-2}–sec^{-1}$ [14, 15]) which equates to 30 Å/year deposition. For non-quiescent this value is $1x10^{-6}$ $g/cm^{-2}yr^{-1}$ or 100 Å/year deposition giving a 130 Å/year system level total deposition rate. The ASIM payload and its component materials exposed to space vacuum (which includes any internal materials within a non-pressurized shell as well as external materials) shall not exceed these limits.

Converting this number into SI units yields 10^{-13} kg/m^2s for quiescent periods. For non-quiescent periods, the total deposition at 300 K on sampling surfaces shall not exceed 10^{-6} g/cm^2yr. This converts into SI units of $3x10^{-13}$ kg/m^2s. Since no special protection methods are foreseen for ASIM during the non-quiescent periods, the payload shall be able to withstand the total contamination. Thus, the average contamination ASIM shall be able to tolerate is $2x10^{-13}$ kg/m^2s. Since the projected lifetime of the ASIM payload is two years, the total amount of contaminant build up on ASIM surfaces is (after two years) $13x10^{-6}$ kg/m^2.

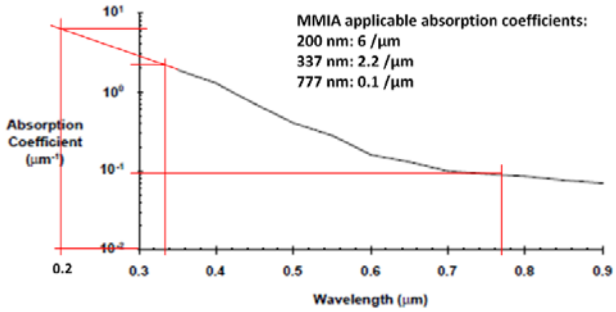


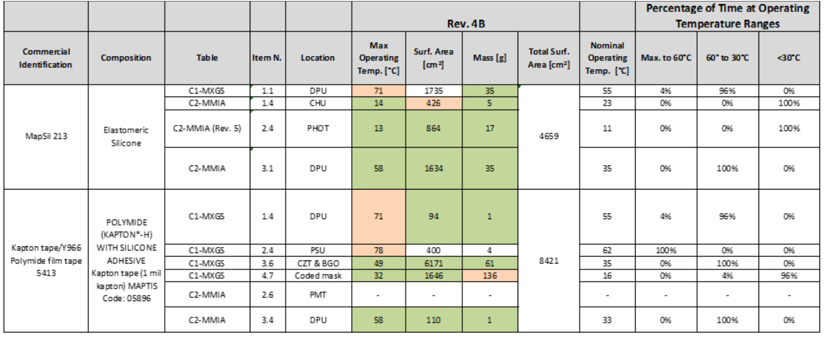
Figure 11 Absorptance profile of "typical" spacecraft contaminants [5]

The only measurable optical effect possible on the MMIA optical systems, to be caused by a molecular layer with a thickness of a few nanometres as estimated above is limited to pure attenuation. The actual attenuation strongly depends on the type of molecules. According to Tribble[5] the typical absorptance profile to be expected in the visible spectrum from the molecular contamination is as shown in Figure 11 above. The profile has been linear extrapolated in order to estimate the absorption coefficient for the MMIA photometer 2 (CWL 205 nm). Given a density of 1.0 g/cm^3 for the molecular layer as recommended in[5], a two-year mission deposition of 1.3x10^{-5} kg/m² corresponds to a layer thickness of 13 nm . Using the absorption coefficients estimated for the specified wavelength and a layer thickness of 13 nm, the expected transmittance T through the molecular layer is thus: T200nm= 0.92, T337nm= 0.97 and T777nm= 1.00. These values have been used for in-orbit molecular transmission loss for the various wavelength and are provided in Table **10**. The MMIA Functional and Performance Analyses[4], has been updated to include the above computed contamination attenuations. The most critical performance parameter, in terms of margin towards compliance to the SRD, is the minimum SNR for Camera 1 when observing Elves. A worst-case contamination attenuation of 3 % still leaves a comfortable margin towards this scientific requirement. In order to comply with ISS level contamination analysis and outgassing and deposition rate requirements a materials list of exposed surface area materials was generated along with the calculated outgassing rates (OGRs) and sent to NASA for each subsystem (see Table **8**) including the MXGS, MMIA, DHPU and MLI materials in the CEPA-MMIA-DHPU MLI interfaces[7]. Table 9 below shows the time at temperature data and the principle materials outgassing sources showing maximum operation temperature , exposed surface area , mass etc. Here also in the right columns the estimated percentage of time at operating temperature range for mapsil 213 and kapton Y966 is also provided and substantiated by real life thermal data from the MMIA output show that temperatures were well within this margin- hence the contamination effect has been shown to be negligible[6]. (see Figure 13)

Table 8 sub system outgassing rates[6]

Sub-System	Weighted OGR (g/s)
MXGS	6.03E-07
MMIA	2.34E-08
DHPU (incl. harness)	7.62E-08
CEPA MLI	2.35E-07
Total	9.37E-07

Table 9 ASIM outgassing sources[6]



					Rev. 4B					Percentage of Time at Operating Temperature Ranges		
Commercial Identification	Composition	Table	Item N.	Location	Max Operating Temp. [°C]	Surf. Area [cm²]	Mass [g]	Total Surf. Area [cm²]	Nominal Operating Temp. [°C]	Max. to 60°C	60° to 30°C	<30°C
MapSil 213	Elastomeric Silicone	C1-MXGS	1.1	DPU	71	1735	35	4659	55	4%	96%	0%
		C2-MMIA	1.4	CHU	14	426	5		23	0%	0%	100%
		C2-MMIA (Rev. 5)	2.4	PHOT	13	864	17		11	0%	0%	100%
		C2-MMIA	3.1	DPU	58	1634	35		35	0%	100%	0%
Kapton tape/Y966 Polymide film tape 5413	POLYMIDE (KAPTON*-H) WITH SILICONE ADHESIVE Kapton tape (1 mil kapton) MAPTIS Code: 05896	C1-MXGS	1.4	DPU	71	94	1	8421	55	4%	96%	0%
		C1-MXGS	2.4	PSU	78	400	4		62	100%	0%	0%
		C1-MXGS	3.6	CZT & BGO	49	6171	61		35	0%	100%	0%
		C1-MXGS	4.7	Coded mask	32	1646	136		16	0%	4%	96%
		C2-MMIA	2.6	PMT	-	-	-		-	-	-	-
		C2-MMIA	3.4	DPU	58	110	1		33	0%	100%	0%

VIII. Cleanliness and contamination control and margins–Dragon contamination molecular and particulate allocation

Table 10 below shows the performance analysis of the MMIA . The SNR=19 value is based on the radiometric budget from the MMIA performance analysis, which considers 3% from in –orbit molecular contamination (from the ASIM contamination analysis T_337nm = 0.97) and Class 700 obscuration which amounts to 2.14% (i.e PAC = 21400 ppm EOL= before launch levels) from this 78 days in ISO Class 8 can be derived.

Table 10 Contamination and SNR requirements for the MMIA

	SRD Min SNR Req	Event	SNR	Particulate (Ground)	Molecular (In-orbit)	Margin
CHU1	15	Elves	19	2.14%	3%	17%
CHU2	100	Lightning	256	2.14%	0%	54%
PHOT1	15	Elves	980	2.14%	3%	88%
PHOT2	3	Elves	446	2.14%	8%	88%
PHOT3	Assuming 100	Lightning	626	2.14%	0%	77%

Table 11 below gives the various radiometric budgets and percentage contamination contributions for various phases of the ASIM payload. For the radiometric budget, the total lens transmission amounts to 0.83 and calculating what the margin in this number is (additional attenuation of the front lens transmission) to reach a SNR 15, gives a value of 17%. Taking additional contamination for the Dragon Space-X CRS-14 phases (ground and in-flight), we consider the 17% as the maximum margin available to maintain ASIM performance. This exercise was performed for all five sensors. With this margin at hand, the calculation of what particulate and molecular contribution amounted to worse case 17% if fully allocated to particulate and to molecular. For particulate, the budget is scaled by the factor of 17%/2.14%. For molecular the total allowable deposition considering density of water is calculated. The CHU1absorption of 2.2 /µm is taken from the absorption profile of "typical contamination "from the 337 nm absorption[5] – see Figure 11 above. The 4.87% from ISS is simply for comparison (using the calculations for 2 years further below). The calculation gives the amount of kg/m^2 that would give 17% attenuation considering water density.

Table 11 contamination contributions

17% for particulate:		165833	mm2/m2	> Level 1000 (148k)	
17% for molecular:					
CHU1 absorption:		2.20E+06	/m	4.87%	\@ ISS
Deposition ISS		2.22E-05	kg/m2		
Density		1000	kg/m3		
CHU1:		7.51E-05	kg/m2		
	Quiscent	**Non-Quiscent**			
g/cm2/y	3.16E-07	1.90E-06			
g/cm2/s	1.00E-14	6.02E-14			
kg/m2/s	1.00E-13	6.02E-13	3.51037E-13		

IX. In-orbit data – thermal and contamination

In order to control in-orbit contamination level on sensitive surfaces and optics the MMIA contains five Optical Assemblies each featuring a front optical element. These elements are: the front lenses of CHU1, CHU2, PHOT1 and PHOT3 respectively, the protective optical filter of PHOT2. These front optical elements are exposed to the particular contamination that exists in the near-ISS environment. To provide ground control with means for de-contamination of the optics a de-contamination subsystem was provided. For each of the Optical Assemblies the MMIA features a heater for contamination boiling-off and a thermistor for acquiring related thermal information. The heaters are mounted on the optical assemblies near the front optical elements(see Figure 12a below) [13], and the thermistors are located in close proximity to the front optical elements to keep the thermal path as short as practically possible.

Figure 12a, b Optical de-contamination design[13] and MMIA in-orbit commissioning temperatures

Figure 12b above (from in-orbit commissioning April 15) shows that the front lens heater design functions well and provided temperatures to boil-off any potential cross contamination depositions from in-orbit effects.

Figure 13 below shows the real in-orbit data (temperature in Celsius) of the MMIA optics and camera over a 2-month period (September20th –November 19th 2019) during operation and shows that operation temperature ranges were lower and within expected % operation ranges. This data is evidence that thermal design and control was successful even with in-orbit environmental effects.

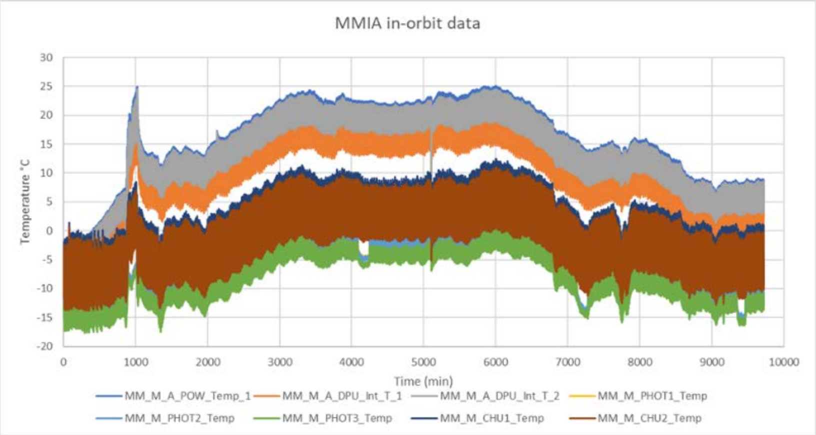


Figure 13 MMIA in-orbit data

X. Conclusion

From the MMIA functional and performance analysis, a 5% attenuation of the optics was considered worse case to maintain performance. This was based upon a 2% attenuation loss for on ground particulate and 3% loss for molecular in-orbit environment contamination. Even given this, the minimum SNR of 15 was obtained with a 17% margin through cleanliness mitigation, de-contamination heaters and thermal control. Comparison of predicted and flight in-orbit data show the ASIM thermal and contamination design to be robust and functional. The ASIM payload continues to produce new, exciting and novel data and images for the scientific, engineering and space communities.

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