

Enhancement in cleanliness and contamination reduction during FPA AIT phase based on non-conformance management

I. Catalan^{*a}, M. Pajas^a, A. Manjón^a, A. Rodríguez^a, A. De Pedraza^a, P. Gallego^a, M.A. Alcacera^a, J.F. Cabrero^a, A.L. Valverde^a, L. M. González^a, V. Fuentetaja^a, A. Balado^a, J. M. Mas-Hesse^b.

^a INTA, Instituto Nacional de Técnica Aeroespacial, Ctra. de Ajalvir, Km 4, 28850 Torrejón de Ardoz, Madrid, Spain

^b Centro de Astrobiología (CAB), CSIC-INTA, Ctra. Ajalvir, Km 4, 28850 Torrejón de Ardoz, Madrid, Spain.

ABSTRACT

PLATO (PLANetary Transits and Oscillations of stars) is a mission of the European Space Agency (ESA) aimed at the finding of a huge number of exoplanets and to characterize them together with their host stars, combining photometric transits information with asteroseismology analysis. For such purpose, 26 flight model telescopes (plus 3 spares) have been manufactured with a total of 116 Charge-Coupled Devices (CCDs) installed on their respective Focal Plane Assemblies (FPAs).

It is noteworthy that in any optical instrument, performance is highly sensitive to any kind of deposited contamination on sensitive surfaces. In PLATO, each FPA gives support to 4 CCDs, each of them with a dimension of 81.18×81.18 mm, with the majority of the sensitive area exposed to the environment through the FPA processing and until its assembly with the Telescope Optical Unit (TOU). Facing this scenario, demanding contamination requirements were imposed at FPA level.

Throughout all the FPAs produced under INTA responsibility, a robust Non-Conformance (NC) process was established based on the ECSS-Q-ST-10-09C. A total of 18 NC's were opened regarding non-compliance with contamination requirements, most of them raised on the first Flight Models, due to issues in the facilities designated for conducting the FPA activities under such stringent requirements.

The objective of this article is to describe the actions taken in response to the non-conformities opened against contamination and cleanliness requirements throughout all the processes on the FPA models and MGSE. It will describe how the effective implementation of these actions led to the successful compliance of the Flight Models delivery.

Keywords: PLATO, FPA, CCDs, Cleanliness, Molecular Contamination, Particles Contamination, cleanroom, non-conformance.

1 INTRODUCTION

PLATO is the ESA's Cosmic Vision Programme M3 mission selected by the Science Programme Committee for launch in 2027. The PLATO mission payload [1] is being developed through a collaborative effort by the international PLATO Mission Consortium (PMC), which comprises a diverse group of research institutions, universities and industry partners from multiple countries. This consortium is responsible for the design, integration and testing of the payload components, ensuring that the instrument meets the stringent scientific and technical requirements necessary for the mission's objectives. Additionally, the ESA has provided significant contributions and support throughout the development process, including technical expertise, funding and oversight, reflecting the mission's importance within the European space science community. The primary goal of the PLATO payload is to perform high-precision photometric observations of thousands of stars to detect planetary transits and stellar enabling the discovery and characterization of exoplanets, particularly those located within the habitable zones of Sun-like stars.

^{*}icatfer@inta.es; phone +34 915201377; www.inta.es

PLATO Payload is composed of 26 cameras, all externally identical (except for the baffles and Front-End Electronics (FEE)), including also the interfaces to the spacecraft optical bench. Mechanically, the central part of the camera is the Telescope Optical Unit (TOU), made of AlBeMet. The six lenses that compose the TOU are all mounted inside this tube. This part serves also as the support for the baffle, that acts both as straylight baffle and as a radiator for the whole camera. The FPA with the detectors is fixed to the TOU by three bipods. The detection chain is completed by using their FEE. More details on the PLATO Camera can be found in [1].

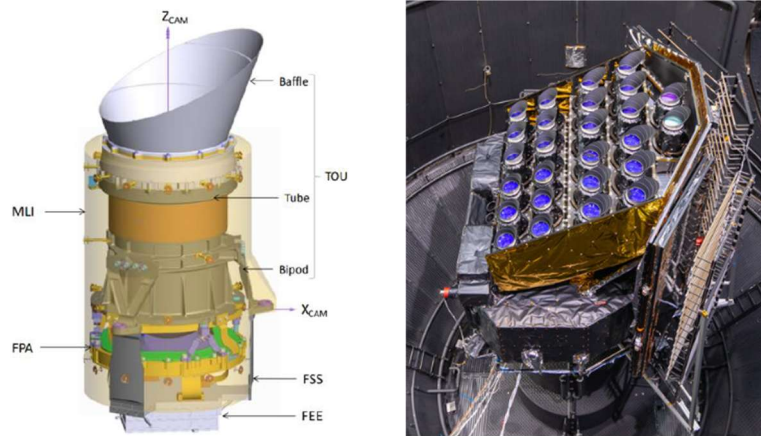


Figure 1. PLATO individual telescope on the left and the 26 large cameras mounted on a five-stepped platform on the right (courtesy: ESA).

INTA has participated in the consortium with several contributions, one of which has been as responsible for the FPA that are integrated into the 26 cameras integrated in the satellite's payload.

The FPA is the structure that gives support to the detectors of PLATO camera. It is composed of:

1. CCD Support Structure: a titanium plate which provides mechanical support to CCDs, as well as protection against straylight and radiation.
2. CCD (x4; model CCD270 [2]): optical detectors with the sensitive area bonded to a Silicon Carbide package including flexi cables.
3. Bipods (x3): to provide the required isostatic interface to TOU. Titanium black coated items.
4. Straylight Mask: it provides straylight and radiation protection to CCDs. Titanium black coated item.
5. Thermal Straps (x4): copper made, which provide the required thermal link between CCDs and TOU.
6. Flexi Feedthroughs (x8): titanium made with a silicon pad, providing mechanical support for the CCDs.
7. Thermal Strap Supports (x8): titanium and Vespel® made, providing mechanical support for thermal straps.
8. TOU interface items: for alignment and holding functions.

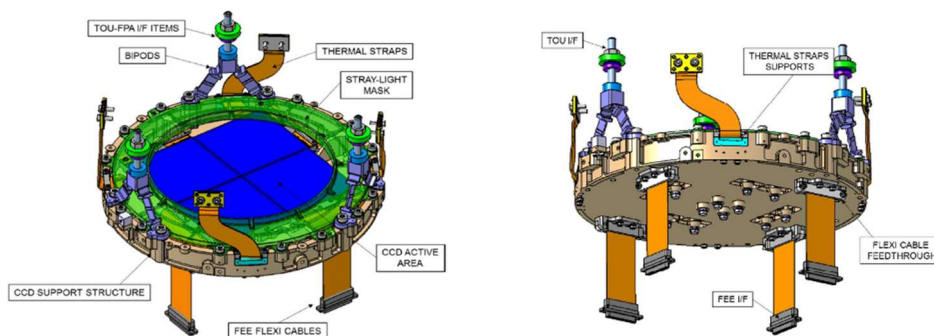


Figure 2. FPA Parts.

There are two types of FPA: Normal and Fast. The components are equal, with the exception of the detectors and the thermal hardware (thermal straps are thicker due to the larger heat dissipation in the F-case). With regard to the detectors, the main difference is: Normal CCDs, optimized for science observations with images acquired every 25 seconds, and Fast CCDs, dedicated to bright targets, fine guidance and navigation, with images every 2.5 seconds.

The challenge of this project, from a technological and management point of view has been the serial production of the Flight models as it was necessary to produce 29 flight telescopes (Flight Model (FM) plus Flight Spare (FS)) with identical performances.

A rigorous management and implementation of disciplines such as Product Assurance have been crucial to address the project objective. This paper focuses on describing the enhancements implemented across the different project phases at INTA to comply with the established cleanliness and contamination requirements.

2 QUALITY ASSURANCE TOPICS

Particularly strict cleanliness and contamination requirements have been imposed on the FPA. The FPA houses the four CCDs which are considered critical items in terms of cleanliness because they are very sensitive to performance degradation caused by contamination on their surfaces and performance loss in these detectors would lead to catastrophic consequences for the project. Not only the detector, but also all the surfaces adjacent to the CCDs, as well as all the Mechanical Ground Support Equipment (MGSE) used, are equally subjected to these very stringent requirements, as they are critical since they can potentially contaminate the sensitive parts.

Consequently, a robust management of the cleanliness and contamination control discipline has been imposed to achieve compliance with the requirement. A detailed FPA Contamination Control Plan in concordance with the specific ECSS-Q-ST-70-01C [3] and the project specification has been established to cover all the FPA unit activities. The contamination control starts from the design phase and have to be taken into account through all phases, up to the FPA delivery. This plan mainly covers: the contamination requirements for the FPA, identification of the contamination sources for FPA and their impact on the FPA performance, establish cleanliness and contamination controls for each phase from the incoming to the outgoing delivery to maintain the required cleanliness levels [4], the contamination budget containing the allocation of contamination level through the splitting of cleanliness requirements during the unit assembly, integration and testing phases until the FPA delivery, philosophy model with regard to the cleanliness and contamination, protection measures to apply and among others activities.

In parallel, a robust Non-Conformance (NC) management process including an effective root cause evaluation has been crucial to reduce the probability of deviation from the requirements since the first model and to meet the short deliveries schedule [5]. The NC process followed is based on the ECSS-Q-ST-10-09C [3]. An NC tracking has been done along all the FPA models assembled and tested by INTA. The implementation of the actions opened within the framework of non-conformances related to cleanliness and contamination requirements has been essential to overcome successfully the serial production.

Throughout all the FPAs processes carried out by INTA, a total 76 NCs (Major and Minor) have been opened. Next figure shows a summary of the distribution per model and a classification based on the type of root cause.

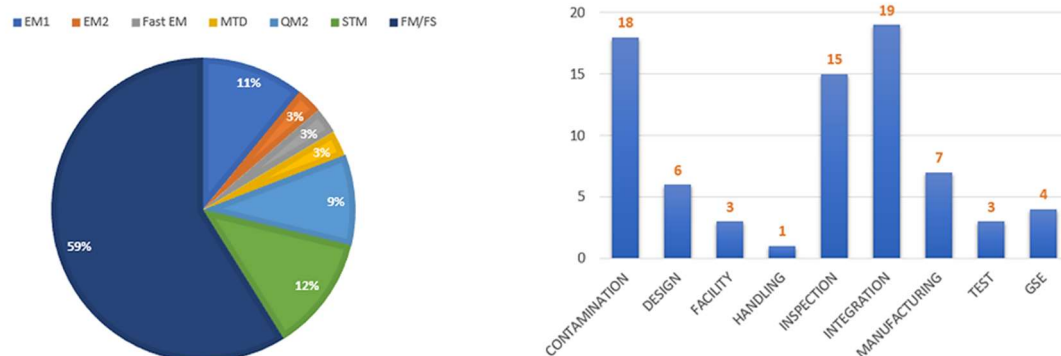


Figure 3. NCs distribution per produced FPA model (by INTA) throughout the project on the left and classification of these by activities.

3 IMPROVEMENTS IN CLEANING AND CONTAMINATION REDUCTION BASED ON THE QUALIFICATION MODEL

The FPA Model philosophy [6] was selected defining the optimum number and type of physical models required to achieve a high confidence in the product verification, with the shortest schedule, and suitable weight of cost and risks.

In the frame of PLATO FPA, the following FPA preliminary models were developed in order to support PLATO verification programs and to have a flight model with the required high reliability for space: Prototype, Structural and Thermal Model (STM), Mass Thermal Dummies (MTDs), Engineering Models (EMs) and Qualification Models (QMs), used to:

- Qualify the design
- Refine Manufacturing, Assembly, Integration, Verification (MAIV) process, procedures, equipment and tools
- Fully validate the large-scale manufacturing and integration process of the Flight model FPAs, consolidating the procedures, schedule and dedicated manufacturing, assembly/test laboratories and facilities.

In the FPA Contamination Control plan, it is described that the EMs and QMs are also foreseen as prototype models to validate the contamination budget and to verify the cleanliness status and monitoring of cleanrooms and facilities.

Ultimately, only the N-FPA QM2 was deployed as a prototype, departing from the initial plan at INTA level. The N-FPA QM2 was totally representative of final flight design, with the exception of the black coating to be applied on the straylight mask and bipods, and only one CCD being fully functional.

This model was fully integrated, including a verification of the detector positions and it was tested at INTA. N-FPA mechanical and thermal qualification test campaign was performed on it, ensuring that the detector positions were not affected by the testing [6]. Also, incoming and intermediate inspections were carried out on it.

The molecular and particulate contribution to the contamination of facilities and processes were monitored by particle fallout (PFO) and molecular witnesses (indirect analysis methodology) during the activities carried on this model. Tape lift method was also used to evaluate the cleanliness status of the mechanical parts before being assembled.

The next tables show, the final accumulative contamination budgets for AIT tasks which were estimated based on the FPA Prototype activities (Table 1), and the final accumulative values of the witnesses that followed the N-FPA QM2, once completed all the activities (Table 2). Although, the activities performed on the N-FPA QM2 are not completely representative with respect to the activities to be carried out on the FPA FM models, the measured levels far exceeded the budgeted estimates and the cleanliness requirements that apply to the FPA upon delivery.

Table 1. Final accumulative contamination budgets for AIT tasks according to the PLATO FPA Contamination Control Plan.

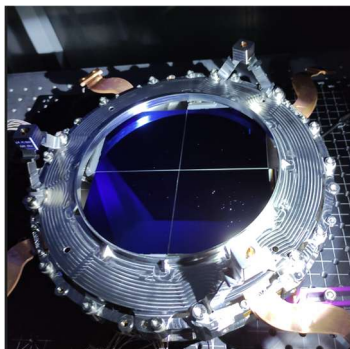
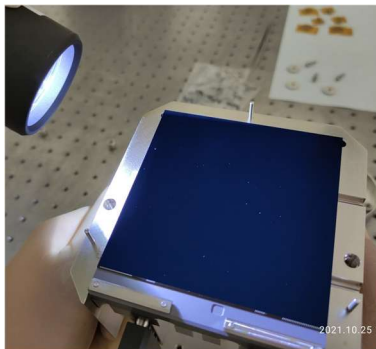
Budget of final cumulative values estimation	
FPA Particulate contamination	168 ppm for the CCDs 109 ppm for the rest of the FPA surfaces
FPA Molecular contamination	3 ng/cm ² for the CCDs 12 ng/cm ² for the rest of the FPA surfaces

Table 2. PLATO Cleanliness requirements for the FPA at the delivery compared to the N-FPA QM2 final accumulative values witnesses after qualification test campaign.

Cleanliness requirements for the FPA at the delivery		N-FPA QM2 cumulative results
FPA Particulate contamination	60 ppm for the CCDs 100 ppm for the rest of the FPA surfaces	220 ppm for the CCDs 379 ppm for the rest of the FPA surfaces
FPA Molecular contamination	20 ng/cm ² , the same requirement for all the surfaces	220 ng/cm ² (mechanical parts) 63 ng/cm ² (CCDs)

In the table below, it is gathered the main improvements identified at this stage to be implemented to the FPA FM/ FS serial production in order to fulfill the delivery acceptance criteria and Product Assurance requirements. The contributions and support provided by ESA have been essential to define these improvements.

Table 3. Summary of improvements to be implemented to the N-FM/N-FS production.

Activity	
Inspection in general	<u>Facility:</u> Cabinet ISO5 inside ISO6 cleanroom; ISO-5 soft-wall portable tent inside ISO 6 and ISO 8. <u>Proposed Improvement:</u> - Mechanical parts cleanliness is ensured, among other methods, via visual inspection by the supplier and subsequently verified by INTA as part of the incoming inspection. However, discrepancies arose between the results of both institutions. To mitigate this and improve reliability, it is established that identical illumination sources and background surfaces must be used for the FPA FM inspections, standardizing the processes across institutions. - To prevent contamination during the inspections, the inspected unit (CCD or complete FPA) should be positioned in a vertical configuration instead of the horizontal position used throughout N-FPA QM2 inspection and cleaning activities shown in the images below.  
Unit integration and optical verification	<u>Facility:</u> ISO-5 soft-wall portable tent inside ISO 6. <u>Proposed Improvement:</u> - Air shower installation at the cleanroom entrance for the FM integration and verification production. - Perform an outgassing assessment of the PVC material used in the ISO-5 soft-wall portable tent. - The efficiency of the covers used throughout the N-FPA QM2 integration and optical verification (see images below) to protect the unit of particulate

	contamination mainly the CCDs, was proven insufficient; therefore, a redesign is required for the FM integration and optical verification production.
	- The use of an electrostatic discharge (ESD) vacuum cleaner to minimize particle contamination, when screwing/unscrewing operations are performed. - General improvement in cleanliness gowning. - Provide recurrent training on cleanliness protocols to personnel involved in AIV activities. - Limit the number of personnel working simultaneously within the integration facility environment. - Although all the precaution are taken to avoid the CCDs contamination, it is not a realistic situation to assume zero particulate contamination, at this stage is considered essential to have a procedure to clean the FMs CCDs active surface in case of contamination to prevent non-conformances with requirements.
Environmental tests*	<u>Facility:</u> ISO 8. <u>Proposed Improvement:</u> - The N-FPA QM2 unit has been bagged (see images below) to protect it from contamination throughout the entire vibration testing sequence, only during certain task such as inspection, the unit remains uncovered. The efficiency of this way of protection has proven inadequate. The acceptance test sequence on FMs needs to be done mandatorily in an ISO 5 environment.

	 - General improvement in cleanliness gowning. - Provide recurrent training on cleanliness protocols to personnel involved in AIV activities.
MGSE inspection and assembly	- Prior to the assembly of the MGSE with the flight components is necessary to clean and to verify the cleanliness by the conscientiously inspection under UV of these parts in order to avoid cross-contamination (particle and molecular) to the FPA sensors and mechanical parts. Included inspections of all the MGSE parts prior to be used with the FPA. [7]. - Each screwing process can result in particle generation, limited as much as possible and established a cleaning way to remove particles.

* Vibration Test, Thermal Vacuum Test and Physical Properties (Centre of Gravity (CoG), Moment of Inertia (MoI) and Mass). Neither Thermal Test, nor CoG and MoI have been carried out at the acceptance campaign for FM.

4 IMPROVEMENTS IN CLEANING AND CONTAMINATION REDUCTION ALONG THE FM/FS SERIAL PRODUCTION

Some of the improvements mentioned in the above section with regard to the facilities, were implemented prior to the FPA FM/ FS production, such as the installation of the air shower at the entrance of the cleanroom where assembly, optical verification, cleaning and inspections activities are carried out; also, cleanliness environment improvement to ISO 5 where the vibration acceptance tests are performed.

Facility cleaning frequency were also increased and some improvements in garments were done. Also, personnel was taken a new training on cleanliness protocols.



Figure 4. Air shower in the left and ISO 5 environment in the right.

New covers were used since the N-FPA FM3, second model integrated by INTA, to avoid particulate contamination during integration activities and transport, although they cannot seal completely with the FPA as they shall not touch the sensitive black coating.

A different design of the cover to be used during optical verification activities was not feasible due to spatial constraints in the setup where the FPA is verified consequently, although the risk of contamination is higher (partly due to the long exposure time of uncovered surfaces) in this phase, attempts were made to mitigate it through increased intermediate inspections and cleaning to be performed not only on the unit, but also on the verification equipment itself to reduce the cross-contamination. In addition, the time that CCDs are exposed open to the environment along the optical verification, need to be reduced.

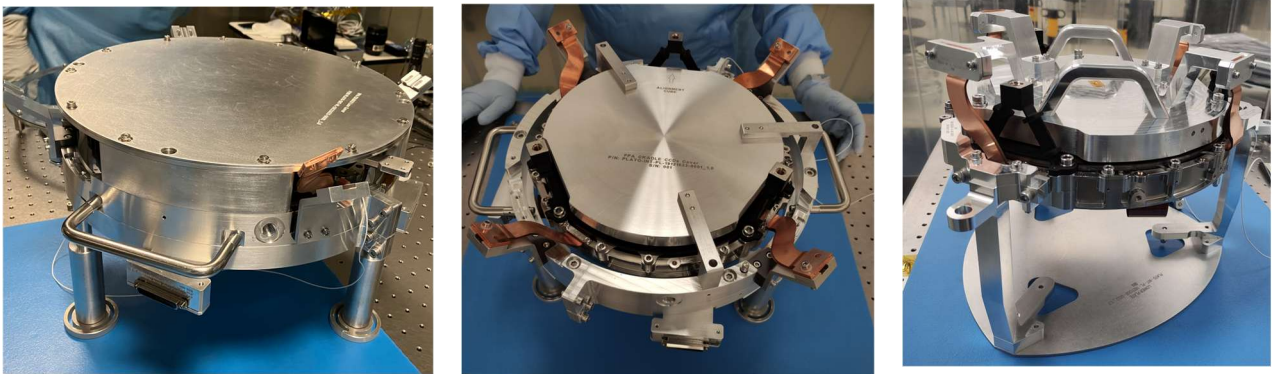


Figure 5. Covers used during FPA assembly activities and transport.

Throughout the serial production of the flight and spares models, despite the implementation of all the above improvements, nearly all FM/FS models were affected by non-conformances due to non-compliance with contamination requirements. It should be noted that the requirement regarding molecular contamination was very tough and the closure of part of these NCs was justified for this reason.

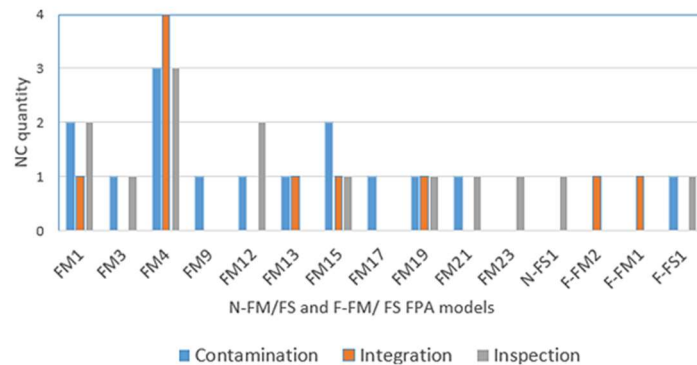


Figure 6. NCs distribution per N-FM/FS and F-FM/FS FPA model regarding contamination, integration and inspection activities at INTA.

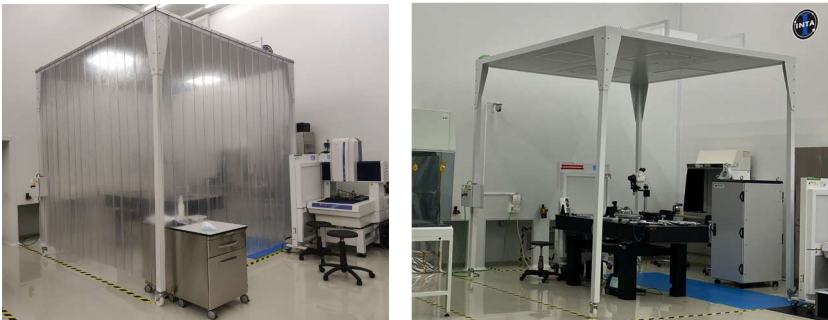
Several non-conformities that affected the first assembled models (FM1 and FM3, mainly) had the major impact in terms of improvements.

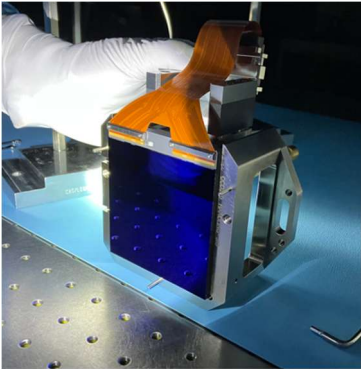
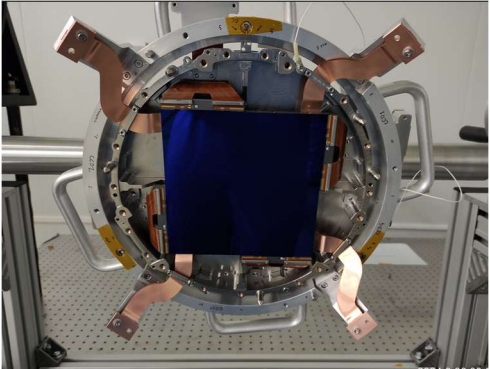
A high number of particles in the CCDs sensitive areas were observed during the visual inspections (under white light in a dark environment) carried out in the models FM1 and FM3. This was not an expected occurrence and led to non-conformities on these models due to non-compliance with cleaning and contamination requirements. In the frame of the Non-conformance Review Boards, it was confirmed by the CCDs manufacturer that the CCDs surfaces have a high tendency to attracts particles, therefore intermediate cleaning of these surfaces throughout the FPA production and before the delivery were established as mandatory.

As results of a rigorous analysis of the root cause by INTA and ESA, more improvements were defined and implemented to minimize the contribution of each contamination sources as much as possible. Furthermore, it wss necessary to assume that cleaning the CCDs active areas at the INTA facilities was imperative which led to the implementation of a training session and the establishment of a cleaning procedure for the CCDs.

4.1 Implementations Regarding Contamination Sources

Table 4. Summary of the main improvements defined with regard to the contamination sources and how had been implemented.

Source	Improvement
Fibers, human skin or human grease	- Improvements in cleanliness gowning. On the left, the one used for the FM1 and on the right the gowning used throughout the rest of the serial production processes.  - Change of the glove type to improve compatibility with IPA
Cleaning material contamination	- Replace plastic bottles for IPA with metallic cans.  - An internal filter was included in the nitrogen guns used to clean by blowing. - Environment where FPA assembly was performed, has been modified. The soft-wall slats made of PVC were removed due to a possible reaction between the material used for cleaning it and the PVC, due to this improvement the particles contamination was considerably reduced. 

Chips and burrs	- To avoid chips and burrs, whenever an element was screwed in place, the area was vacuumed during assembly. 
Dust in the environment, particle cross contamination during the inspection and the cleaning process	- Whenever feasible, inspections and the FPA cleaning were carried out with the CCDs active area oriented vertically. [5]  
Cross Contamination in the optical verification process	- Although contamination of the CCDs surfaces by minor grease residues accumulating on the mechanism and guides of the optical verification equipment was ruled out, a protective cover was installed as an additional risk mitigation measure to address even minimal risk.   - Also, a cleanliness inspection to confirm that there was no additional grease was done before any verification activity.

4.2 Implementations Regarding Contamination Cleaning

Since the FM4 production, an in-house CCDs (focused on the active areas) cleaning procedure was established, being developed as a result of the training supplied by Te2V (CCDs manufacturer). The procedure was always applied during

the Mandatory Inspection Points (MIP), after an optical verification process, before and after vibration acceptance test acceptance and during the outgoing inspection of the FPA model performed for delivery.

It is the only approved method by ESA to remove particles from these surfaces. It consists of blowing the CCDs, which are positioned in a dedicated flipping jig structure, by means of an ionizing air gun with filtered, dry, high-purity compressed nitrogen, while simultaneously vacuuming the detached particles using a cleanroom-grade, ESD-protective vacuum cleaner.

Once cleaned, sometime remnant objects persisted on the CCD surfaces, which aren't necessarily particles. The experience gained throughout production made it possible to distinguish whether a finding could impact performance or is insignificant and can be left as is.

In summary, the implementation of a well-defined and versioned step-by-step cleaning sequence has been key to achieving the requirements across the many cleaning campaigns performed on the FPA units.



Figure 7. From left to right: Flipping jig; FPA mounted on flipping jig ambient light on; FPA mounted on flipping jig ambient light off.

4.3 FPA AIVT Process time evolution

The analysis of the evolution of all the AIVT time of all flight models integrated and tested at INTA reflected a considerable minimization in time and maximization in quality of processes [8]. The FM1 is the flight model that has taken the most time among all the FPAs. Then, optimization and refinement of procedures and good practices give a reduction in total time for the remaining flight models. In fact, considering that from FM17 onwards, the reduction in time with respect to the FM1 is more than 51% which is quite remarkable and noteworthy.

5 CONCLUSION

PLATO Mission is an unusual space project since it has involved a high-rate serial telescopes production. Serial production has allowed us to implement the emerged lessons learned from the initial models, preventing the recurrence of the same failures or issues and improving all activities. Thanks to a robust Non-Conformance management process which includes a rigorous and efficient root cause evaluation, the improvements were identified at the beginning of the production.

In this paper, it has presented a description of these improvements and how they have been implemented across the different project phases being effective to result in compliance of the strict cleanliness and contamination requirements imposed to the PLATO FPA, in addition these improvements have helped us to reduce the execution time of the activities which altogether has enabled to reach the serial production goals in time.

It should also be noted that the entire assembly, verification, inspection, and cleaning line for CCDs and FPAs, facilities, and personnel, have been permanently established at INTA for future missions with similar industrial scale and performance requirements.

ACKNOWLEDGEMENTS

Authors acknowledge that the successful development of PLATO FPA was enabled by the extensive collaboration across all components of the PLATO Mission Consortium (PMC) and ESA, encompassing participants from multiple countries. The development of PLATO at INTA has been funded by the MICIN/AEI/10.13039/501100011033 grants PID2019-107061GB-C61/C62, and the MCIU/AEI and ERDF/EU grants PID2023-147338NB-C21/C22.

REFERENCES

- [1] Rauer, H. et al, “The PLATO Mission”, Experimental Astronomy, 2025, vol 59, pg. 26 <https://doi.org/10.1007/s10686-025-09985-9>
- [2] Pratlong, J. et al, Innovations in imaging technology at Teledyne e2v to support future visible, NIR, UV, and x-ray applications, SPIE Optics + Optoelectronics 2024, DOI: 10.1117/12.3018898
- [3] European Cooperation Space Standardization <https://ecss.nl/>
- [4] I. Catalan et al., “Particulate and Molecular Cleanliness control of the FPA for PLATO Mission”. Optical Sensors 2025, Proc. of SPIE Vol. 13527,135271G; <https://doi.org/10.1117/12.3058515>
- [5] Catalán I. et al, “Product Assurance Activities for PLATO Focal Plane Assembly”, IAA Symposium on Safety, Quality and Knowledge Management in Space Activities, International Astronautical Congress (IAC), 2025, Conference paper, <https://doi.org/10.52202/083095-0048>
- [6] M. Pajas, et al., “Model philosophy of Focal Plane Assemblies for PLATO Mission”, SPIE Optics + Optoelectronics 2025, DOI: 10.1117/12.3058420
- [7] A. Rodríguez et al., “Handling, Cleanliness and Transport of Mechanical Ground Support Equipment integrated with Focal Plane Assemblies for PLATO ESA Mission”, SPIE Optics + Optoelectronics 2025, <https://doi.org/10.1117/12.3058531>
- [8] P. Gallego, et al., “Learning curve resulting from serial flight models production of PLATO focal plane assemblies”, SPIE Optics + Optoelectronics 2025, DOI: 10.1117/12.3058425