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The PLATO camera

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Abstract—**PLATO (PLAnetary Transits and Oscillation of stars) is a candidate for the M3 Medium-size mission of the ESA Cosmic Vision programme (2015-2025 period). It is aimed at Earth-size and Earth-mass planet detection in the habitable zone of bright stars and their characterisation using the transit method and the asterosismology of their host star.**

That means observing more than 100 000 stars brighter than magnitude 11, and more than 1 000 000 brighter than magnitude 13, with a long continuous observing time for 20 % of them (2 to 3 years). This yields a need for an unusually long term signal stability. For the brighter stars, the noise requirement is less than 34 ppm.hr$^{-1/2}$, from a frequency of 40 mHz down to 20 µHz, including all sources of noise like for instance the motion of the star images on the detectors and frequency beatings.

Those extremely tight requirements result in a payload consisting of 32 synchronised, high aperture, wide field of view cameras thermally regulated down to -80 °C, whose data are combined to increase the signal to noise performances. They are split into 4 different subsets pointing at 4 directions to widen the total field of view; stars in the centre of that field of view are observed by all 32 cameras. 2 extra cameras are used with color filters and provide pointing measurement to the spacecraft Attitude and Orbit Control System (AOCS) loop. The satellite is orbiting the Sun at the L2 Lagrange point.

This paper presents the optical, electronic and electrical, thermal and mechanical designs devised to achieve those requirements, and the results from breadboards developed for the optics, the focal plane, the power supply and video electronics.

Keywords -exoplants; photometry; camera; wide field of view

I. INTRODUCTION

PLATO (PLAnetary Transits and Oscillation of stars) is a candidate for the M3 Medium-size mission of the ESA Cosmic Vision programme (2015-2025 period). It is aimed at Earth-size and Earth-mass planet detection in the habitable zone of bright stars and their characterisation using the transit method and the asterosismology of their host star.

The mission concept is based on very high accuracy, very long period photometry of stars. The key contribution of PLATO arises from the observations of stars brighter than covered by current space transit surveys (CoRoT, Kepler) and its wide (~50%) coverage of the sky. It has been proposed by a consortium of many European and non-European countries and submitted to ESA in 2011 for the M1-M2 missions. The future proposal for M3 will be endorsed by a new consortium with mostly the same partners but a different share of responsibilities.

The PLATO consortium is responsible for the development of the payload and of the science ground segment. The payload, consisting of cameras and electronic units, will be delivered to ESA for later integration inside the Payload Module (PLM).

This paper presents the main results of the definition phase studies done on the cameras by the different partners of the consortium, over the 2010-2011 period.

II. MISSION AND SPECIFICATIONS

A. Mission

The basic goal of PLATO is to detect and characterize a large number of planets and planetary systems. This will be obtained by observing the signatures of the planets transiting in front of their parent stars. Combined with ground-based follow-up observations such as high resolution spectroscopy, this will enable a full characterisation of the planetary systems. The primary targets of PLATO are therefore stars that are bright enough for such characterisation. The same observation data and ground-based follow-on will also be used to confirm or measure the star's fundamental parameters and provide data on the full planetary system.

Exoplanetary transits with all characteristics (depth, period) in front of various types of stars in the habitable zone of bright G-K stars will be investigated, leading to a full knowledge of exoplanet populations and allowing us to relate planet characteristics to central star properties for an unbiased statistical sample. In particular, telluric exoplanets in the habitable zone will receive special attention. The mission design must be such that a statistically significant number of those planets can be studied. PLATO will provide a measurement of their mass with < 5% accuracy and 2 % accuracy for their radii. Once these parameters are known for a large enough number of planets, it will give a more accurate vision of the typical bulk composition and interior structure of rocky, icy and gas giant planets, of how those depend on the environment and on the basic link between interior and atmosphere.

In addition to these main goals involving the observation of a sample of bright stars, PLATO will also perform a more extensive survey of exoplanetary transits in front of a very large number of fainter stars. Also, in complement to the seismic analysis of planet host stars, asteroseismology of the many other stars present in the field of view will be used for a more complete study of stellar evolution. Observations of stars of all masses and ages, all across the HR diagram, including members of several open clusters and old population II stars, will be obtained for this purpose.

B. Main Specifications

These science objectives will be met using long uninterrupted high precision photometric monitoring of large star samples. To maximize the surveyed sky area and hence the number of monitored stars, the mission will combine different phases of 'step & stare' and long monitoring of successive fields. The latter could each last from 2 to 3 years.

The photometric requirements associated with the different samples of stars observed are given in Table I.

TABLE I.   PHOTOMETRIC REQUIREMENTS FOR PLATO

Photometric requirement	Long monitoring (4 300 deg²)		Step and stare
	Number of stars	*Magnitude*	*(22 000 deg2)*
34 ppm.hr$^{-1/2}$	22,000	9.8-11.3	85,000
80 ppm.hr$^{-1/2}$	267,000	11.6-12.9	1,000,000
80 ppm.hr$^{-1/2}$	> 1,000	8	3,000
80 ppm.hr$^{-1/2}$	> 60,000	11	180,000

Gaps in the data result in a reduction of the probability to detect successive planetary transits, and are also responsible for sidelobes in the stellar oscillation power spectra. They must be minimized.

Any source of non-photonic noise must remain at least 3 times below that of the photon noise, in the frequency range 0.02-10 mHz. Below 0.02 mHz, the non photonic noise level is allowed to rise gradually, to reach a maximum of 50 ppm µHz$^{-1/2}$ in the Fourier domain at a frequency of 0.003 mHz for magnitude 11 stars.

III. PAYLOAD CONCEPT

The requirement of uninterrupted observations during periods longer than a year leads to an orbit around the Sun-Earth system L2 Lagrange point, and the need for a 90° satellite rotation around the instrument axis every 3 months to avoid the risk of Sun illumination inside the instrument and limit in the same time the size of the sunshield. Processing of the data series is simplified thanks to a design theoretically invariant in a 90° rotation.

The science requirements above lead to an instrument with the simultaneous and usually conflicting goals of a large pupil for high resolution photometry and a very wide Field of View (FoV) to observe enough stars. The instrument concept is based on a multi-telescope approach, involving a set of 32 wide FoV (900 deg²) 'normal' cameras working at a cadence of 25 sec to monitor stars fainter than magnitude 8, plus 2 'fast' cameras (with the same FoV as the normal cameras) working at a cadence of 2.5 sec to observe stars in the 4 to 8 magnitude range.
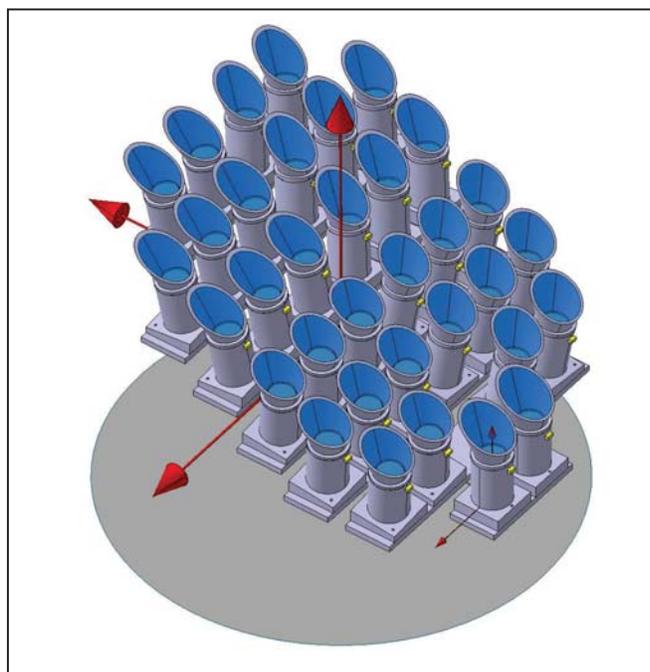

Figure 1.   General accomodation of the payload.

In particular, the multi-camera concept shows easier feasibility and a significant mass reduction compared to a single large camera concept. 32 are needed to reach the overall pupil of the instrument, and are fit out on one single optical bench (see Fig. 1), which is a part of the satellite.

The very wide field of view, close to 1100 square degrees for each camera, comes from the high number of stars and the magnitude range required by science. The use of many cameras allows for an optimisation between the field of view and the pupil size of the overall instrument. On one hand, if all cameras are aligned along the same line of sight, the pupil size is maximized, and the field of view is minimized. On the other hand, if cameras are aligned along adjacent fields of view, the

total field of view of the instrument is multiplied by the number of cameras, but the pupil size is minimized and equal to that of a single camera. After a trade-off, we have accommodated the cameras among 4 sets of 8, each set pointing in a particular direction, with overlapping fields of view (see also Fig. 2):

- the central field (300 deg^2) is seen by the all the 32 cameras, leading to an equivalent pupil diameter of 678 mm,

- a second part (250 deg^2) is seen by 24 cameras, with an equivalent pupil of 585 mm,

- a third part (735 deg^2) is seen by 16 cameras, with an equivalent pupil of 480 mm,

- the fourth part (950 deg^2) is seen by only 8 cameras, with an equivalent pupil of 340 mm.
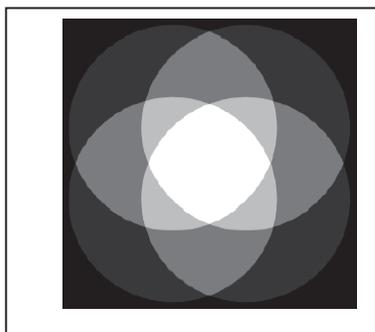

Figure 2.   Example of a figure caption.

The overall field of view of the instrument with such an accommodation is higher than 2200 deg^2, with a pupil diameter larger than 340 mm.

In addition, the high resolution photometry requires high pointing stability: this is the purpose of the 2 Fast cameras to deliver high frequency pointing error information to the satellite Attitude and Orbit Control System (AOCS). They are also used for science, as they can deliver photometric data for very bright stars in narrower spectral bands.

Each camera has its own Focal Plane Assembly (FPA), its own detector readout electronics (Front End Electronics –FEE), powered by remote power supplies, the Ancillary Electronic Units (AEU). These units are specific for Fast or Normal cameras: for instance, there are Fast FEEs, Normal AEUs, and so on.

The AEUs are located inside the satellite service module, below the optical bench, in order to minimize the thermal load and insure the best thermal stability on the optical bench, which is critical to maintain the alignment of the cameras between them. 4 Normal AEUs provide the power to 2 cameras in each set (for reliability reasons), and one Fast AEU is dedicated to the 2 Fast cameras.

Photometric measurements are affected by:

- the readout noise, directly linked to the readout rate and subject of a trade-off between noise and readout time,

- the background noise, coming from straylight and detector dark current, limited by the use of a baffle in front of each camera and by detector cooling,

- the jitter noise resulting from the displacements of the star images on the detectors, limited by the use of the Fast camera data in the AOCS loop.

The camera changes in temperature also affect the light flux at different points:

- the diameter of the diaphragm which defines the telescope aperture,

- the shape of the telescope Point Spread Function (PSF),

- the detector quantum efficiency and output amplifier gain.

Will limit these effects:

- a temperature control of the camera structure,

- a thermal isolation of the camera against all temperature change sources (optical bench, power supplies),

- a constant power consumption of the FEEs on time scales longer than the exposure cycle,

- an on-ground correction of the jitter noise through the knowledge of the PSF.

In addition, a final processing of the results provided by the normal cameras which are observing the same stars at the same time is possible and minimizes the effects of temperature variations.

Data sent out from the FEE is then processed in several digital units. The final goal of this data processing is to provide light-curves that fulfil the noise requirements. Due to the limited telemetry bandwidth, those light-curves must be performed on-board.

All the data is first processed by the Digital Processing Units (DPUs). Each DPU (one per two cameras) has to run photometry algorithms:

- a weighted mask method which can reduce the pollution induced by the presence of a parasite close to a star. It makes it possible to put more weight in the center of the star image and less weight in its tail, so the photometric measurements mostly represent that of the observed star. The mask characteristics must be updated periodically to prevent the star from going out due to the differential aberration,

- a line spread function fitting which is an attractive alternative to aperture-based photometry.

Then all data is transmitted to the Instrument Control Unit (ICU) used as a concentrator from the 16 DPUs to the spacecraft. The ICU can add processing which needs an overall view on the instrument since it has access to data from all cameras.

IV.   CAMERA DESCRIPTION

A. Optics and detection

The wide FoV of a single camera is obtained by a fully dioptric optical design, optimised in a large wavelength range to maximise the number of photons received, put in front of a FPA of 4 large, back-thinned CCD detectors, for better quantum efficiency.

The 32 Normal cameras have full-frame detectors, while Fast cameras have the same detector operating in frame-transfer mode (and only half sensitive area), to be compliant with the need an image cadence of 2.5 seconds for the AOCS loop.

The FEE is located below the FPA, thermally and mechanically decoupled thanks to a flexi-PCB. It commands and controls the activities of the four detectors, which are read one by one to avoid large current peaks and then to smooth the power consumption. Moreover, the 4 sets of cameras are also read one by one for the same reasons.

B. Mechanical and thermal architecture

The detectors must be strongly cooled to limit their dark current which is also a source of noise. As the accommodation of the 32 + 2 cameras on the optical bench of the satellite does not allow sufficient cooling from the back (because of the satellite service module) or from the sides (because of the other cameras), the only possibility is by radiating towards the sky. The FPA is then thermally strongly coupled to the structure of the camera, which is highly conductive and evacuates the heat to its optical baffle, also connected to the camera structure and used as radiator with a large view factor on the sky.

The optics has the particularity that its both ends are very cold: the last lens is in front of the cold FPA, and the entrance window faces the deep sky. The telescope optical design is then optimized at a nominal temperature of -80 °C at its temperature reference point (close to the pupil plane), with low axial gradients (structure highly conductive), authorising temperatures lower than -60 °C with margins at the detectors.

To guarantee this temperature, an active temperature control slightly heats the structure. Each camera has its own temperature control in a small range around -80 °C, authorising by this way a small focus adjustment in flight by a slight temperature change.

Each camera breaks down in (from top to bottom in Fig. 3):

- an optical baffle, also used as thermal radiator,

- an Telescope Optical Unit (TOU) with 6 lenses and a front window, supported by a mechanical structure, also used as a thermal bus,

- the FPA with the 4 detectors, supported by the TOU structure,

- a set of 3 titanium bipods, attached to the structure, ensuring the mechanical and thermal interface with the optical bench of the satellite,

- non mechanically attached to the camera, but part of it, the FEE for the control of the detectors.

The mass of the camera, as multiplied by 34 (32 + 2) in the mass budget, is very critical. To be compliant with the allowed mass, the camera structure is made in AlBeMet, which has particularly good stiffness vs. density and thermal conductivity vs. density ratios.

Depending on the camera type and size of baffle, the cameras are between 70 and 80 cm high (including baffle and FEE).
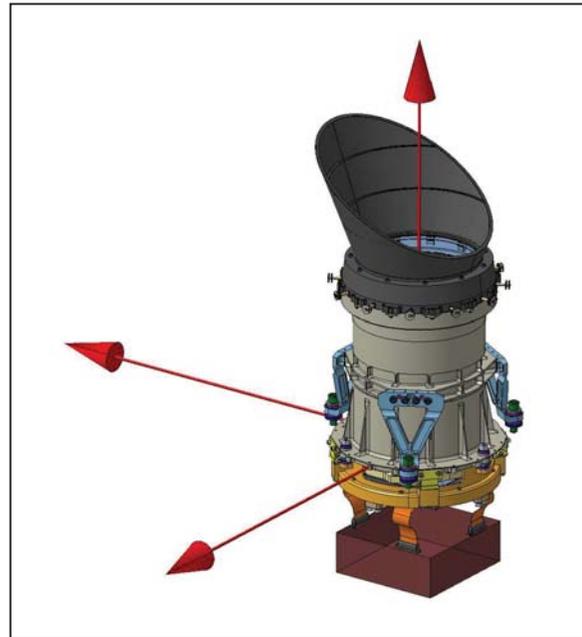

Figure 3.   View of the camera.

C. Electrical

The electrical architecture is designed to reduce the noise sensitivity (EMC) with proper grounding and the noise sources by synchronizing the different processes. ESD constraints are also taken into account in the global design and integration process.

The grounding scheme encompasses all the electronic units involved in the different readout functions of the camera, from the power-supplies to the CCDs inside the focal plane.

The main functions of the different electronic units are:

- AEU: to provide analog and digital voltages, from 3.3V to 28V.

- FEE: to provide chronograms for CCD readout and video chain processing, bias voltage regulation, house-keeping management and digital interface with the DPU.

- FPA: to provide a support structure the CCDs.

The electrical architecture is based on the following concepts:

- To provide a common ground plane from the power-supply to the CCD. There is mechanical and electrical ground planes between the FPA and the FEE, connected together at the FEE side.

- Each CCD has its own substrate (ground) reference and bias voltage lines.

- The FPA is electrically decoupled from the TOU to avoid parasitic electrical signal coupling with the thermal regulation of the TOU.

- The flexi-cable between the AEU and the FEE is grounded with connections allowing high frequency filtering.

- The power supply architecture is designed to reduce the noise and the drift of the CCD bias voltages. A first filtering is performed inside the AEU and a second stage filtering inside the FEE. Then bias voltage regulators as near as possible to the flexi-cable are used to provide bias voltage to the CCDs.

A global synchronization scheme is implemented to reduce cross talk between the different FEEs, AEUs and the TOU active thermal control.

Inside the Fast AEU, a specific unit distributes different synchronization signals all from a unique reference high frequency clock (with a temperature and power supply compensated crystal oscillator) with cold redundancy. Two kinds of synchronization signals are distributed, high frequency signals to get unique and stable exposure time and low frequency signal to get stable phasing between all the processes.

To simplify the electrical interface, all the synchronization signals are sent via LVDS interface (same hardware of the Space-Wire).

V. CAMERA SUBSYSTMS

A. Telescope Optical Unit (TOU)

The design of the TOU is led by a team involving Italy, Swiss, and Sweden, and coordinated by Istituto Nazionale di AstroFisica (INAF) - Osservatorio Astronomico di Padova.

1) Optical design

The optical concept of the telescope [1] is based on a six fully centered, spherical lenses design, except the first one, which features an aspheric surface. The maximum deviation from the best-fit sphere is about 1.050 mm, which was validated by industry. A front window protects the lenses from radiations and limits the sensitivity of the telescope to the thermal environment. The inner pupil, which limits the flux, is well delimited by a circular diaphragm located on the third lens, and guarantees a real entrance pupil diameter of 120 mm.

The Fast TOUs have the same design as the Normal. They only differ in the transmitted spectral band, and thus in a dedicated coating.

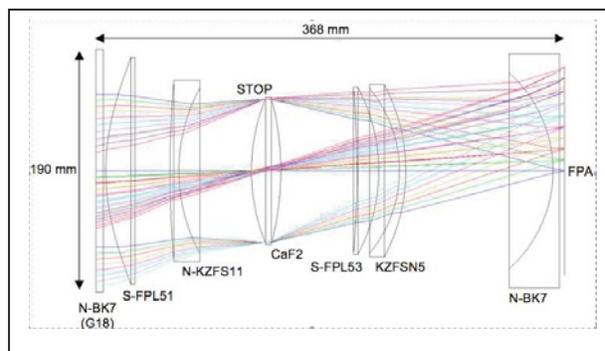Fig.4 shows the optical layout of the TOU and table 2 lists the main optical parameters.

Figure 4.   TOU optical layout

TABLE II.   OPTICAL PARAMETERS

Spectral range	500 – 1000 nm
Entrance pupil diameter	120 mm
Working F/#	2.06 @ 700 nm
Field of view	1151.5 deg^2
Image quality	90% enclosed energy < 2x2 pixel^2 over 1108.3 deg^2
Maximum field distortion	5.043%
Plate scale	15 arcsec.pixel^{-1}
Optical elements weight	5 kg
Working temperature	-80°C

The polychromatic enclosed energy over the full Field of View is shown in Fig. 5. The weights of the wavelengths have been set taking into account the detector quantum efficiency and the G0 star spectrum.
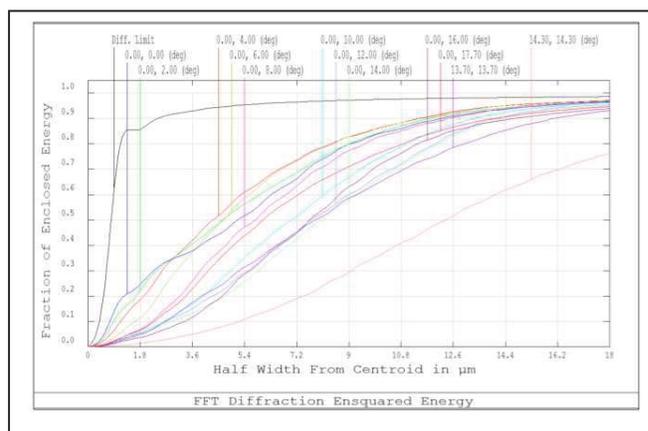

Figure 5.   Ensquared Energy.

90% of the ensquared energy is contained in 2x2 pixels^2 (pixel pitch is 18μm) in the field of view 13.7x13.7 deg^2.

2) Materials

The lens materials have been selected after a study of radiation effects on glass for an 8 years lifetime at L2 point. This study has concluded that the darkening of glass due to radiation environment at L2 only appears in the first millimeter of the first lens glass. The other lenses are protected by the entrance window and by the telescope structure provided that this structure does not present important holes. Moreover, the fluorescence due to the irradiation of the lenses is emitted in the UV band of the spectrum and hence it will be easily filtered out to avoid contamination in the focal plane. As result of this study, glasses BK7 G18 (radiation-hardened version of BK7) is chosen for the entrance window. For the other lenses, more usual glasses can be used. The total transmission loss will be lower than 0. % per year in L2 point, for a front window.

Another specific study has been carried out for CaF_2. CaF_2 is a material alleged to show brittleness and high susceptibility to temperature changes. Dedicated tests [2] have been done on CaF_2 blanks (non-polished parallel-plane disks of thickness 26 mm and diameter 120 mm) to observe the response of this material when subjected to thermal and shock stress comparable to a launch through a Soyuz-Fregat type vehicle. One blank was tested under vibrations at Bern University and then tested in thermo-vacuum in at CNES Toulouse facility, with temperatures cycling from 4°C to -100°C, and a gradient of 0.2°C/min. Visual inspection after tests confirmed that no damage or evident changes in mechanical properties had occurred.

All the lenses are attached to the AlBeMet tube through barrels with the same coefficient of thermal expansion as that of their lens' glass.

3) Thermal analyses

Two preliminary thermal analyses have been carried out. The first case assumes a uniform variation of the TOU in the range -90°C to -80°C. The optical system has 2K of tolerance without the need of refocusing. With a temperature change of 10K the nominal performances are still recoverable by applying a defocus through the three resistors: the defocus is linear with the temperature inside the explored range and has a value of 11 μm.K^{-1}. In the second case the effect of a thermal gradient along the TOU tube was analysed. The optical system maintains the nominal performances with a temperature gradient of 5K without the need of refocusing, while the performances are recoverable by applying a defocus in the case of a 10K gradient.

4) Stra light and ghosts

Each telescope is equipped with a baffle around the front window lens used as a radiator and for limiting the factor of view of the first lens and avoiding direct view of the sunshield by the inner surface of the baffle. The two Fast TOUs have the same baffle. Conversely, the Normal TOUs have four different baffles the set they belong to.

A Zemax non-sequential model of the TOU has been built to study the levels of straylight and the presence of ghosts. It takes into account the scattering properties of the structure, the blackened lens borders, lens roughness, dust deposition, lens coatings, FPA front window and makes the trade-off with or without baffle. The model shows that the average straylight is within specifications (<3 ph.px^{-1}.s^{-1}, while the requirement is $\sim$<20 ph.px^{-1}.s^{-1}). Concerning the ghosts, a detailed study was dedicated to point-like ghosts created by double reflection on the detector and the front flat window. These ghosts may be easily confused with a real star, creating a "false positive". The study shows that the ghosts have a quasi-linearly decreasing intensity going from the centre of the FoV towards the border, vanishing for vignetting effects for position angles greater than 7°. The central intensity of the ghost will depend obviously on the coatings of the detector and of the front window, and on the spectral type of the source. A more detailed simulation with a typical star field of PLATO should be conducted to evaluate the impact of these point-like ghosts on the "false positive" detection.

5) Breadboard results

A TOU prototype BreadBoard (BB) [2] has been designed and produced during the phase A of the project, to validate assembly, integration and test procedures, verify their time-compatibility with respect to industry framework (since the realization of the TOUs is intended to be assigned to industry), and test the on-axis system performance in ambient (20 °C, 1 atm) and thermal vacuum conditions (-80°C, 0 atm). The BB consists of a set of 6 custom made lenses as close as possible to final design and a mechanical structure equivalent to TOU in terms of thermal behaviour.
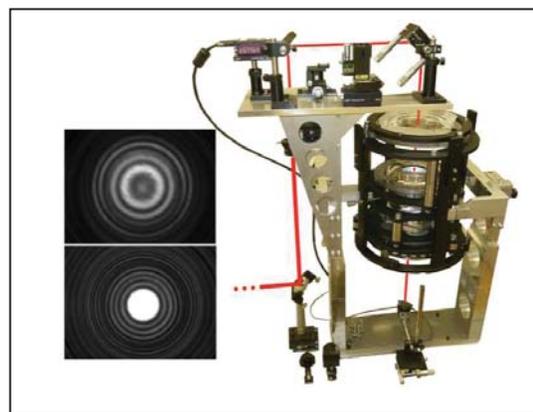

Figure 6. The handling used to hold the BB during the integration. Such structure allows the required 180 degrees rotation of the BB itself, to insert the lenses, starting from L3, always from the top of the structure. On the left are shown the back reflected spots used to check the alignme nt quality.

It was assembled, aligned (fig. 6) and tested in warm conditions at INAF Padova laboratory [3], and then tested in cold environment at SELEX Galileo SpA facilities (interferometry with a Zygo, PSF measurement, Hartmann test). The BB activities confirm the feasibility of the alignment of the TOU in a time-slot estimated in 2-3 days, a reasonable amount of time if this had to be performed for the 32 TOUs by industries. Both optical and mechanical components behaved extremely well, allowing meeting alignment requirements in warm, maintaining the alignment also in the transition from warm to cold, where the performance improved of an amount comparable to the expected one.

B. *Focal Plane Assembly (FPA)*

The design of the FPA is led by the Departamento de Astrofisica de Centro de Astrobiología (CAB) of the Instituto Nacional de Técnica Aeroespacial (INTA) with the support of the Lidax company.

The FPA has different functions:

- Handle and position the CCD on a flat plane within a flatness requirement of 50µm on all the sensitive surface of the CCDs at the right distance from the last TOU lens (optical back focal distance).

- Insure the thermal and mechanical interfaces with the TOU to maximize the thermal conductivity and the mechanical stiffness.

- Insure the electrical decoupling with the TOU.

- Insure parasitic light and radiations protections via mechanical plates or hood surrounding the CCDs in proper position. This hood insures also dust protection during AIT operations.

The Fast and Normal FPA have the same mass, volume and accommodation. They support 4 CCDs and share the same internal and external interfaces, except for the thermal straps sized for each case.

It has a 90° symmetry with the outputs of the 4 CCDs each on one side of the FPA. This way, after rotation of the satellite, star images fall on the next CCD but at the same place with respect to the CCD axes (in particular the 'smearing' axis) as the previous one.

The FPA mechanical design is shown Fig. 7. All the main parts are made of the same material as the telescope tube, AlBeMet. Each of the 4 CCDs is isostatically mounted thanks to flexure blades to compensate for the different coefficients of thermal expansion between the structure and the detector package made of SiC, on an AlBeMet support structure. Studs are placed under the CCD to achieve the required flatness of the sensitive surface. This support is attached to the TOU structure thanks to a stiff interface ring via 3 points allowing global tilt and piston adjustment of the FPA/TOU. Four thermal straps insure the right thermal conductivity between FPA and TOU.

Electrical conductivity is broken at the mechanical/thermal interface via electrical insulator thin film (CHOTHERM).

The CCD, developed by e2v under an ESA contract, integrates different known technologies on the same chip.

They have an extremely large sensitive area of 4510x4510 pixels of 18 µm pitch, yielding a sensitive area of 81.18x81.18=6590 mm^2. In all, the sensitive area of the complete instrument is 0.9 m^2. The flatness is better than 40µm on the whole sensitive surface and the mean plan of the pixel is measured on each CCD for mechanical adjustment inside the FPA.

They are buttable along 3 sides of the chip, with a flexi-cable integrated on the SiC mechanical package on the last side. The flexi cable is directly connected to the FEE under the FPA. A PT100 thermal probe is also integrated on the SiC package with electrical connection inside the flexi-cable to monitor the detector temperature. The readout register with outputs at both ends is implemented on the flexi-cable side,

The CCD is operated at 4 Mpix.s^{-1} with 28 e$^-$ rms noise. Two reference outputs (with the same implantation as the actual outputs but no connection with the real register) can be used in noisy environment.

The full well capacity is around 1 Me$^-$ thanks to a specific SiO oxide barrier thickness. High quantum efficiency (mean over the bandwidth wavelength > 70% on 450-950nm) is achieved thanks to back-thinning, and the expected PRNU lies within few %.

For the Fast CCDs, an aluminum shield is deposited on the one half of the sensitive surface along the output register to build a memory zone. Thus, the 4 Fast CCDs sensitive areas cover the center quarter of the FPA plus another 'spread' quarter forming the shape of a cross.
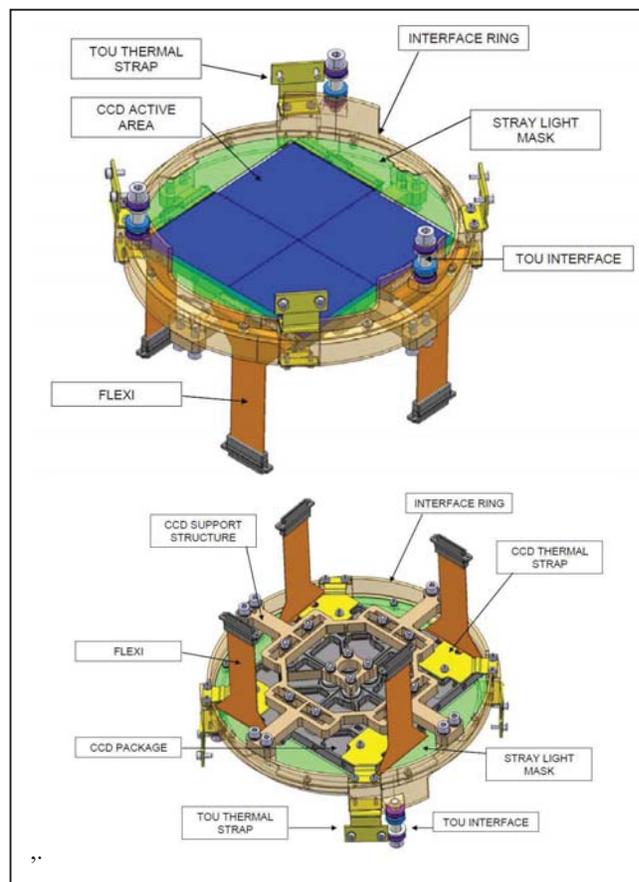

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Figure 7. Mechanical design of the FPA. Front (top) and rear (bottom) view.

The integration procedure, in particular its duration, has been validated on a prototype built against the standard procedures of the flight models.

C. Front-End Electronics (FEE)

At each FPA is connected a FEE to perform CCD and house-keeping readout. Normal and Fast FEEs share the same interface with minor differences and have common module architectures.

The 32 Normal FEEs are under the responsibility of the Mullard Space Science Laboratory (MSSL), while the 2 Fast FEEs are under the responsibility of Commissariat à l'Energie Atomique (CEA). However, the design is defined inside a mixed English/French team.

The electronic architecture mostly consists in 3 boards with their interfaces assembled inside one mechanical housing.

- One board is dedicated to a second stage of power-supply voltage filtering.

- The second one gathers all the digital functions of the FEE, to perform (via an FPGA) the 4 CCD readout (clock sequencing, video signal chain management) and the communication with the Digital Processing Unit on a 100 MHz Space-Wire link.

- The third one is dedicated to the analog functions of the FEE, to perform the 4 CCD bias voltage regulation, video signal processing and digitization.

The main differences between the Fast FEE and the Normal FEE come from the CCD readout, where the Fast CCDs are read simultaneously unlike the Normal CCDs which are read one after the other. In both cases, the two outputs of each CCD are read simultaneously.

All the design is based on space qualified components.

1) Normal FEE.

Here also, due to the large number or cameras, mass and power-consumption reductions are strong constraints for the design.

Analog multiplexors are used to select the CCD output to read (1 over 4) and then reduce the number of video chains. To reach the noise and speed performances, two 16- bits ADC are used in parallel operation. So each CCD output is then divided in odd and even columns. The odd and even columns are sent alternatively to one of the two ADC to avoid differential drift. Classical filtering and clamp CDS are implemented.

Two Space-Wire links @ 100MHz are used to send the data to the Digital Processing Unit (and command reception) with 20% margins on the data rate.

A breadboard is currently under tests, and will be coupled to a CCD when available.

2) Fast FEE

The Fast FEEs must read 4 CCDs simultaneously at a high frame rate (2.5 s for 40 million pixels) and also remains in the given budgets.

This implies to make 8 video chains work in parallel. The required noise allows the use of integrated video chain inside a single chip (2 video chain, clamp and 14-bits ADC). On the same way, 8 Space-Wire links @ 100 MHz are used in parallel to send all the data to the Fast DPU. The power supplies

filtering stage is dimensioned for a higher peak power consumption.

A breadboard is currently under tests, and will be coupled to a CCD when available.

Table III gives a brief summary of the FEE specifications. The size of the FEEs is about 185x193 mm, the Fast FEE being slightly higher (100 mm) than the Normal (70 mm).

TABLE III.   OPTICAL PARAMETERS

FEE	Readout rate (Mpix.s^{-1})	Noise (e$^-$.MHz^{-1})	Noise bandwidth (MHz)	Bias noise (µV)	Power (W)	Mass (kg)
Normal	2x4	48	20	30	7	1.3
Fast	8x4	114	20	30	13.8	1.4

D. Ancillary Electrical Unit

The AEU provides power to a high resolution CCD camera system which is highly sensitive to converter noise currents. So the main design drivers are:

- First, the very strict requirement on common mode noise and ripple. A total of 125 uV rms over the 10 Hz-50 MHz frequency range for the 6 output voltages provided by the AEU is required, which means about 20 µV rms on each voltage at CCD level.

- Secondly, the AEUs are located on the service module, meaning a distance to the FEEs (on the OB) of up to 5 meters.

Whilst every effort has been made to minimize the sensitivity of the FEE to AEU line noise, one of the main sources of noise is always the power converter, and this noise is usually difficult to remove unless the overall EMC design is constrained from the start.

In order to respect these constraints, a design based on a half bridge converter topology, synchronized with each other, associated to filters (input and output) and linear post regulation has been implemented.

1) Normal AEU.

There are 4 Normal AEUs,. Each contains 8 independent DC/DC converters, one for each Normal FEE.

The Normal AEU design is based on a development of two types of modules, the Normal FPGA Module and the Converter Module. In total, the Normal AEU consists of an assembly of 2 Normal FPGA Modules with one in cold redundancy and 8 Normal Converter Modules.

The functionalities of the Normal FPGA Module are:

- managing the SpaceWire and clock signal (provided by the Fast AEU),

- ON/OFF, limitation and protections status and commands,

- generating the synchronisation frequency of the converters,

- managing the internal housekeeping interface, digital conversion and transmission of the HK to ICU over the Space Wire network.

The functionalities of the Normal DC/DC Converter Module are:

- supplying power to the 6 outputs voltages across Half-Bridge converter cell,

- input protection of the converter function,

- input and output filtering,

- linear post regulation,

- managing the internal housekeeping interface and measurements.

A breadboard has been built which confirms the predicted noise level at the AEU output. An end to end test including the Normal FEE breadboard and the CCD remains to be done to assess the performance at image level (i.e. including the 5-m long cable and FEE input filters).

2) Fast AEU.

The F AEUAEU has 2 main functions. The first one is, as for the Normal AEU, to supply power to the Fast FEEs. A second one is to provide the synchronization signals required for the mission.

As regards the power supply, the Fast AEU architecture is based on two fully independent chains for delivering power to the 2 Fast FEEs. It consists of the assembly of 2 FPGA Modules and 2 Converter Modules. The functionalities of the Fast FPGA and Fast DC/DC Converter Modules are the same as those of the Normal FPGA and Normal DC/DC Converter Modules.

To avoid drifting cross-talk (noise inside the white noise and also spurious lines in the Fourier spectrum) due to de-synchronization process during the FPA readout and to have the same exposure time for all the Cameras, a specific electronic unit included in the Fast AEU provides different synchronization signals:

- a high frequency (50 MHz) clock to the FEEs for CCD readout and Space-Wire links management,

- two low frequency signals (pulses) to the FEEs for starting the FPA readout, one at 2.5s for the Fast FEE and one at 6.25 s for the Normal FEE,

- a high frequency (10 MHz) clock for the Fast and Normal FPGA Modules of the AEUs,

- a low frequency signal to the SVM to synchronize PWM activation of the TOU thermal control.

It is made of two independent systems used in cold redundancy to manage the different synchronization signals.

E. Integration and tests

The large number of cameras does not allow full end-to-end test on all cameras. Our strategy is to fully test and characterize the three main components of each camera (TOU, FPA and FEE) and to fully test the camera in thermal vacuum only for one camera out of four. The other cameras will be tested under ambient conditions of temperature and pressure, in the LAM facilities.

Optical ground support equipment for the tests at room temperature will be developed by the Center for Astronomy and Astrophysics of the University of Lisbon (CAAUL).

The CCDs are tested one by one to measure main characteristics like dark current, gain, full well capacity, pixel response non-uniformity.

The CCDs are mounted and aligned inside the FPAs. Geometrical measurements are made only at room temperature provided that behavior at low temperature is validated on the first models.

The TOUs are fully integrated and optically tested to get back optical distance in thermal vacuum.

The FEE are tested in thermal conditions to measure the different sensitivities of the video chain.

Then the three components are integrated together. The mechanical assembly of the TOU and FPA is made with CCD sensitive surface and TOU focal plane positioning measurements, and the effect of temperature is taken in account via mechanical, thermal and optical modeling validated on the camera qualification model.

Depending on the camera (one over four), the optical set-up is verified at ambient or nominal working temperature. The noise and cross-talk are also measured.

VI. MAIN BUDGETS

The power budget of the instrument yields a nominal power consumption lower than 800 W including 20% of uncertainties, compliant with the allocated power. In this budget, 82 W are dedicated to the temperature control of the 34 cameras, while each camera has a power budget lower than 8.5 W for normal and 17 W for fast. The digital electronics and the power supplies represent close to 400 W.

The mass budget of the instrument yields a nominal mass of 600 kg, including 20 % of uncertainties, compliant with the allocated mass. In this budget, each camera, Normal or Fast, has a mass budget lower than 16 kg. The digital electronics and the power supplies represent close to 60 kg.

The telemetry budget of the instrument leads to a nominal telemetry volume of 103 Mbit.day^{-1}, including auxiliary header overhead, compliant with the allocated value. The telemetry issued from Normal cameras is the major part of the budget.

VII. CONCLUSION

One of the main difficulties with the development of the PLATO cameras lies with the large number of equipments to provide associated with the very high level of photometric performance required.

The studies made during the definition phase have lead to a design compatible with the mass and power requirements of the PLM, and modular enough so that a share of activities can

be set up. A sound calibration and correction strategy has been devised to limit as much as possible the individual performance needs of the single cameras.

With a proper manufacturing strategy and organisation, we think we have demonstrated that all the equipments can be assembled and delivered in the timeframe or the mission.

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