CHEOPS Instrument thermal design and test

Romain Peyrou-Lauga
ESA, ESTEC, Noordwijk, The Netherlands

Giordano Bruno
University Bern, Switzerland

CHEOPS - CHaracterizing ExoPlanets Satellite (CHEOPS) is the first ESA Science Small Mission (S1-Mission) dedicated to the study of exo-planetary transits by means of ultrahigh precision photometry on bright stars already known to host planets. The main science objective will be to study the structure of exoplanets with radii typically ranging between 1 to 6 Earth radius orbiting bright stars. The science payload, subject of this paper, consists in one Instrument including a compact on-axis Ritchey-Chrétien telescope of useful diameter of approx. 30 cm, and a single, frame-transfer, back-illuminated CCD detector.

The Spacecraft is 3-axis stabilized injected on a Sun-Synchronous Orbit at a nominal altitude of 700 km and 06:00 am Local Time at Ascendant Node. The Instrument will point anti-Sun direction +/- 60°. A sunshield protects the focal plane radiator from direct sun illumination providing it with a stable thermal environment. During its orbit, the spacecraft is slowly rotated for maintaining the focal plane radiator oriented towards cold space, enabling a passive cooling of the detector to below 233 K and ensuring its thermal stability (<10 mK).

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>Airbus DS</td>
<td>AIRBUS Defence and Space</td>
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<tr>
<td>BCA</td>
<td>Baffle and Cover Assembly</td>
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<tr>
<td>BEE</td>
<td>Back End Electronic</td>
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<tr>
<td>BEO</td>
<td>Back End Optic</td>
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<td>BOL</td>
<td>Beginning of Life</td>
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<td>CCD</td>
<td>Charged Coupled Device</td>
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<tr>
<td>CDR</td>
<td>Critical Design Review</td>
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<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Plastic</td>
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<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt</td>
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<tr>
<td>EOL</td>
<td>End of Life</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>FEE</td>
<td>Front End Electronic</td>
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<td>FPA</td>
<td>Focal Plane Assembly</td>
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<td>FPM</td>
<td>Focal Plane Module</td>
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<tr>
<td>GMM</td>
<td>Geometrical Mathematical Model</td>
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<tr>
<td>IR</td>
<td>Infra-Red</td>
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<tr>
<td>MLI</td>
<td>Multi-Layer Insulation</td>
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<tr>
<td>OB</td>
<td>Optical Bench</td>
</tr>
<tr>
<td>OH</td>
<td>Optical Head</td>
</tr>
<tr>
<td>rms</td>
<td>root mean square</td>
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<tr>
<td>S/C</td>
<td>Spacecraft</td>
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<tr>
<td>SEM</td>
<td>Sensor Electronic Module</td>
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<tr>
<td>SSM</td>
<td>Second Surface Mirror</td>
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<tr>
<td>STR</td>
<td>STar Tracker</td>
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</tbody>
</table>

1 Thermal engineer, ESA, TEC-MTT, romain.peyrou-lauga@esa.int.
2 Thermal engineer, University of Bern, giordano.bruno@space.unibe.com.
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\[TB/TV\ (\text{test}) = \text{Thermal Balance (test)}\]
\[TEL = \text{Telescope}\]
\[TMM = \text{Thermal Mathematical Model}\]
\[VDA = \text{Vacuum Deposited Aluminium}\]

I. Introduction

CHEOPS (CHaracterizing ExoPlanets Satellite) is the first ESA Science Small Mission (S1-Mission) dedicated to the study of exo-planetary transits by means of ultrahigh precision photometry on bright stars already known to host planets. The latest evolution of the Instrument thermal design is presented in the next chapters followed by a synthesis of the Instrument thermal verification by test which started with an early Structural and Thermal Model thermal balance test 2 years before the Proto-Flight Model thermal cycling and thermal balance tests which was completed early 2018. The Instrument will be delivered and integrated to the Platform during spring 2018, with a full Spacecraft Thermal Vacuum Test foreseen in June 2018. CHEOPS project targets a launch readiness by December 2018.

II. Overview of CHEOPS mission and Spacecraft

A. Overview of CHEOPS satellite

Figure 1 presents an artist view of CHEOPS Spacecraft. The Instrument is mounted on top of the Platform, on a stiff panel and is radiatively and conductively decoupled from the Platform. One of the main Platform requirements is to support the functionality of the Instrument and its photometric precision. The main implications for the Platform are related to the pointing capabilities and the thermal environment for the Instrument. This includes the provision of the large Sunshield (which supports 3 body mounted solar panels) to protect the Instrument focal plane housing and radiators from solar illumination. 2 Instrument electronic boxes are located inside the Platform and thermally controlled by the Platform. Besides, the Platform provides the Baffle support structure, so as this latter can be fully decoupled from the Telescope.

B. CHEOPS orbit and attitude

- **Orbit**

  CHEOPS will be injected on a Sun synchronous Low Earth Orbit (LEO) with a local time at ascendant node (LTAN) fixed at 06:00 a.m. and an altitude of 650 km. Such an orbit presents a good compromise between a large sky coverage for science objectives, a stable thermal environment and a relatively easily accessible orbit (for a dual launch). Winter Solstice corresponds to the eclipse season (which lasts about 3 months) represents the hot case for the Instrument due to the combination of the high Sun flux (the Earth is close to the perihelion) and the maximum albedo flux received by the Instrument, particularly above the South pole area which is Sun illuminated at this period of the year.

- **Attitude**

  The satellite attitude and pointing have been defined on the basis on the targeted observation field, which in turn must respect the Earth stray light exclusion angles. At any moment of the year, CHEOPS instrument must be able to point any star up to 60° away from the anti-Sun direction. The pointing angle can be any combination of azimuth / elevation angle.

  The immediate consequence is to accommodate the Instrument on the anti-Sun side, and to shade its radiators with a Sunshield covering all possible Sun aspect angle (up to 60° away from the telescope axis). As a result, the Instrument is most of the time in the shade of the Sunshield and little sensitive to direct Sun flux (and eclipse).
Besides this, a variable spin allows the radiators to avoid or limit as much as possible any field of view with the Earth. For low off axis pointing, a slow rotation around the Telescope axis is used to avoid albedo and Earth Infra-Red flux on the radiators, as illustrated in Figure 2. However, for Instrument large off axis pointing, significant radiator field of view with the Earth occurs inevitably once per orbit – always above one of the Polar regions. Similarly, the Telescope has also a large view factor with the Earth once per orbit at the same moment. Although the Earth is occulting the targeted star at this precise moment, no specific spacecraft depointing is foreseen, and Instrument thermal control will have to cope with such external flux peaks.

Figure 2. Example of CHEOPS attitude.

III. Overview of CHEOPS Instrument

A. Overview of CHEOPS Instrument

The Instrument includes the following parts:

- **2 electronic boxes** (visible in Figure 3)
  - Sensor Electronic Module (SEM)
  - Back End Electronic (BEE)
- **The Telescope and Focal Plane Module assembly** which is composed of:
  - the Instrument Structure
  - the Telescope and Optical Bench (OB)
  - the Focal Plane Module (FPM) which encompasses the Focal Plane Assembly (FPA) and the Front End Electronic (FEE), including their radiators (visible in Figure 4)
- **The Baffle and Cover** (visible in Figure 4, with the cover closed)
- **Some Platform parts:**
  - BCA Collar (provided by the Platform) (visible in Figure 4)
  - Star Track OH (STR-OH) (provided and managed by the Platform, but mounted on the Instrument)

Figure 3 and Figure 4 presents the different parts of the Instrument. The Telescope is inside the Structure tube and is not visible in the pictures.
B. Instrument unit dissipations

Table 1 provides the Instrument dissipation when it is operational. All dissipation are equal to 0 when the Instrument is switched off.

Table 1. CHEOPS instruments dissipations

<table>
<thead>
<tr>
<th>Units inside the Instrument volume</th>
<th>Dissipation (Operational)</th>
<th>Unit located in the Platform</th>
<th>Dissipation (Operational)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Plane Assembly (FPA)</td>
<td>0.3 W</td>
<td>Sensor Electronic Module (SEM)</td>
<td>3.1 W</td>
</tr>
<tr>
<td>Front End Electronic (FEE)</td>
<td>3.5 W</td>
<td>Back End Electronic (BEE)</td>
<td>11.6 W</td>
</tr>
</tbody>
</table>

C. Instrument thermal-mechanical interface with the Platform

Figure 5 below illustrates the interface between the Instrument and the Platform.

- **BCA collar**
  In green in Figure 5, the BCA collar is a rigid structure protruding from the Platform, which the Instrument Baffle is mounted on. It allows alleviating the mechanical load on the Instrument, knowing that the Baffle does not have any stringent co-alignment requirement with the Telescope. The BCA collar is insulated with MLI (Platform responsibility) and is passively thermally controlled.

- **Platform top panel**
  In blue in Figure 5, one can see the Platform top panel, which is a rigid sandwich panel. Besides supporting the BCA collar, it provides the mechanical interface for the OB + Structural tube assembly. The 3 titanium bipods (2 on the structural tube and 1 on the OB) provide a low conductance between the Instrument and the Platform to limit heat leakage. As the Instrument has its own MLI, no extra radiative insulation is added on the Platform top panel underneath the Instrument. Expected temperature difference are not expected to exceed 40°C and the Instrument MLI is assessed to be sufficient for the radiative insulation. It is noteworthy there is no dissipative unit mounted on the Platform top panel, in order to avoid generating internal thermal gradients which would have detrimental thermo-elastic effect and potentially affect the Instrument pointing stability.
• **Sunshield**

In red in Figure 5, the Sunshield is an extension of the Platform. It supports the solar panels and a small panel for the antennas. It guarantees a permanent shadow for the Focal Plane radiators whatever the Instrument pointing is, providing it remains no more than 60° away from anti-Sun direction. No parts of the Instrument interfaces mechanically with the Sunshield, except gold-coated titanium low conductive electrical grounding straps (visible in Figure 9). As the Sunshield panels can be very hot when Sun illuminated at high incidence angle, their inner sides are insulated with MLI, which faces Instrument FPM housing MLI.

### IV. CHEOPS Instrument thermal requirements

CHEOPS instrument thermal requirements are summarised in **Table 2** and illustrated in Figure 6.

**Table 2. CHEOPS Instrument operational thermal requirements.**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Temperature requirement</th>
<th>Temperature stability requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPA</td>
<td>-40°C or less</td>
<td>Better than 10mK (peak to peak)</td>
</tr>
<tr>
<td>FEE</td>
<td>as low as possible to limit thermal losses towards the CCD (set point at -10°C)</td>
<td>Better than 50mK (peak to peak)</td>
</tr>
<tr>
<td>Telescope</td>
<td>as low as possible to limit thermal losses towards the FPM and limit heating power consumption (set point at -10°C)</td>
<td>Thermal stability during science better than +/- 5K</td>
</tr>
</tbody>
</table>

**Figure 6. Overview of CHEOPS Instrument thermal requirements.**

• **CCD detector**

CCD detector thermal stability requirement is particularly demanding with maximum 10 mK peak to peak over 1 imaging sequence (which can last potentially several orbits). Moreover, for noise reduction purpose, the CCD has to be kept at temperature lower or equal to -40°C.

• **Front End Electronic (FEE)**

FEE thermal requirement is a bit less stringent as the stability has to be better or equal to 50 mK over 1 imaging sequence. The FEE temperature do not affect its performance, but it is kept as low as possible to limit thermal losses towards the detector.
**Telescope**
Thermal stability required to the Telescope Tube is maximum 10 K in order to contain the overall Telescope structure thermal breathing which directly influences the Instrument Point Spread Function (PSF) and the optical performances.

V. CHEOPS Instrument thermal control architecture

A. Instrument internal thermal interface

**Figure 7** below illustrates the internal thermal interface between the different parts of the Instrument. The Baffle has no mechanical connection with the Telescope which helps to better control the Telescope within a restricted temperature range whereas the baffle internal surfaces have a large view factor with cold Space and the Earth and may consequently experience cold and varying temperature.

![Diagram of Instrument internal thermal interface](image)

**Figure 7.** CHEOPS Instrument internal thermal interface

B. Instrument thermal insulation

As illustrated in Figure 6, the overall Instrument is wrapped with a 20 layer MLI, made of a combination of:
- Black kapton 160 XC for the external layer, which ensures the required electrical conductivity
- VDA-kapton-VDA for the 5 next outermost layers, which can be hot when Sun illuminated
- VDA-mylar-VDA for the next layers (except the innermost one)
- Glass fibre spacer in between all layers
- VDA-kapton-VDA for the innermost layer

An additional internal 20-layer MLI blanket (VDA-mylar-VDA layers with dacron spacer) is inserted between the Structural Tube and the Telescope Tube.

**Figure 8** shows the Instrument backside, without the MLI blanket. In the same figure is visible the FPM hood, on which are mounted the FPM radiators. The CFRP OB connects the FPM with the structure. The Instrument is mounted on the TV chamber baseplate. **Figure 9** shows the Instrument with the MLI blanket, covering the FPM hood and radiators backside. The gold-coated grounding straps are thin titanium foils, which connect the radiators to the spacecraft structure. They pass through the MLI blanket through dedicated MLI slits.
C  FPA thermal design

FPA thermal design has been designed to be able to cool down passively the CCD at (at least) -40°C. As illustrated in Figure 10 the FPA thermal control includes:

- High conductance/thermal inertia path between the detector and the radiator, using mainly a silver thermal strap (visible in Figure 11). The flexibility of the thermal strap allows the mechanical decoupling between the detector and the radiator. All interface connection include indium thermal filler to guarantee the best conductance possible.
- High thermal inertia capacitor (in AlBeMet, a beryllium alloy) visible in Figure 12 to help temperature stabilization.
- Gold coating on the external surfaces facing the FEE assembly or the FPM housing as illustrated in Figure 12.
- Thermal insulation from the radiative and conductive environment: MLI is used on the backside of the radiator to reduce the parasitic heat loads. Titanium washers are used to decouple the FPA cold block from the FEE structure, which operates at warmer temperature. Vetronite washers are used to decouple the radiators from the FPA hood on which the radiators are mounted.

- The CCD is eventually coupled to a radiator (shown on the right side in Figure 13) which remains always in the shadow of the Sunshield. This radiator is covered with 10 mil Silver / Teflon SSM, which offers a high Infrared emissivity and a rather low solar absorptivity with reduced degradation over time. High conductive aluminium alloy (6063-T6) has been chosen to maximise heat spreading. The total surface is 0.063 m².

- An operational PID law controlled heating line is used to complement the passive thermal control to keep the CCD to its set point with the requested stability.

When the Instrument is OFF, a survival heater line with a simple ON/OFF control loop is controlled by the Spacecraft to keep the FPA above its non-operational temperature limit. The ceramic heaters (visible in Figure 14) are located on the capacitor (clamped and glued with high conductivity NuSiL glue) close to the survival thermistors (shown in Figure 12).

![Figure 13. Instrument FPA and FEE radiators](image1)

![Figure 14. Instrument FPA survival heaters](image2)

C FEE thermal design

The FEE thermal control presents similar features as the FPA (as seen previously):
- High conductance link to its radiator.
- High thermal inertia with an AlBeMet capacitor.
- Thermal/Mechanical decoupling
- Thermal insulation
- Operational PID law heating line
- Survival heating line

In addition, a structure made of beryllium, on which the FEE PCBs are mounted, contributes to increase the thermal inertia of the system for the PCBs temperature stabilization. This structure is visible in Figure 12 with its gold coating.

The FEE radiator (visible on the left side in Figure 13) is covered with 10 mil Silver / Teflon SSM and has a surface equal to 0.057 m².

![Figure 15: FEE thermal design](image3)
C Telescope thermal design

The Telescope is located inside the volume of the Structural Tube. The purpose of the Telescope thermal control is to ensure a good radiative decoupling of the Telescope Tube from the outer Structural Tube, allowing:
- a reduced temperature excursion, caused by the Sun and Earth heat loads in hot condition
- saving heating power in cold condition when the instrument is permanently in the shadow of the sun shield and of the Platform.

These objectives are achieved by means of two MLIs, one around the Structural Tube, the other around the Telescope Tube. Several kapton heaters foils (operational + survival heaters) are attached on an aluminium foil around the Telescope Tube in a radiative configuration to keep both the operational and survival set points. They are presented in Figure 17 and Figure 18. Operational heaters are controlled with PID law. Figure 19 and Figure 20 show the different thermistors of these heating lines.

![Figure 16: Inside view of the Telescope, with the main mirror (M1) and the back side of the M2](image1)

Figure 17: Telescope heaters unfolded

Figure 18: Telescope heaters wrapped (GMM)

Figure 19: Instrument TEL operational thermistors

Figure 20: Instrument TEL survival thermistors
C Instrument heating lines synthesis

Table 3 presents the overall operational heating lines of the Instrument, which are managed by the BEE. The operational lines use a Pulse-width modulation (PWM), whose modulation of the duty cycle is made through a PI controller with narrow acquisition time. This, together with the high thermal inertia, allows the FPM to comply with the very demanding thermal stability requirements.

Table 3. CHEOPS Instruments operating heating lines

<table>
<thead>
<tr>
<th></th>
<th>Power @ 31V [W]</th>
<th>Heaters R. [Ω]</th>
<th>Set-point [°C]</th>
<th>Sensors</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPA</td>
<td>7.60</td>
<td>126.4</td>
<td>-40</td>
<td>PT1000</td>
<td>Pulse-width modulation duty cycle controlled</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>through PI algorithm</td>
</tr>
<tr>
<td>FEE</td>
<td>15.6</td>
<td>61.6</td>
<td>-10</td>
<td>Thermistors:</td>
<td></td>
</tr>
<tr>
<td>Telescope +X</td>
<td>19.8</td>
<td>48.6</td>
<td>-10</td>
<td>2252 Ω @ 25°C</td>
<td></td>
</tr>
<tr>
<td>Telescope -X</td>
<td>19.8</td>
<td>48.6</td>
<td>-10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All the survival and annealing lines have their own redundancy and use an ON /OFF law. The annealing line has the scope to heat up the Instrument detector up to +45°C, in order to repair possible micro damages caused by the space radiation, generating hot pixels.

Table 4 presents the overall survival heating lines of the Instrument. They are permanently enabled and are managed by the Platform.

Table 4. CHEOPS Instruments survival and annealing heating lines

<table>
<thead>
<tr>
<th></th>
<th>Power @ 31V [W]</th>
<th>Heaters R. [Ω]</th>
<th>Set-point [°C]</th>
<th>Sensors</th>
<th>Controller</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPA survival</td>
<td>15.8</td>
<td>60.8</td>
<td>-45 / -40</td>
<td></td>
<td>ON / OFF</td>
<td>FPA capacitor</td>
</tr>
<tr>
<td>FEE survival</td>
<td>34.2</td>
<td>28.1</td>
<td>-15 / -10</td>
<td>3 x thermistors:</td>
<td>FEE capacitor</td>
<td></td>
</tr>
<tr>
<td>Telescope survival</td>
<td>26.4</td>
<td>36.4</td>
<td>-20 / -18</td>
<td>10 kOhm @ 25°C</td>
<td>TEL</td>
<td></td>
</tr>
<tr>
<td>FPA annealing</td>
<td>59.3</td>
<td>16.2</td>
<td>+45°C</td>
<td></td>
<td></td>
<td>FPA capacitor</td>
</tr>
</tbody>
</table>

VI. Instrument Thermal Vacuum Test

A. Overview of the Instrument models and Thermal Vacuum Tests

Three models in total have been used for the verification through thermal test:
- Instrument Structural and Thermal Model (STM)
- Instrument Proto-Flight Model (PFM) with Focal Plane Module Engineering and Qualification Model (FPM-EQM)
- Full Instrument Proto-Flight Model (PFM), which integrates all flight parts and components.

The purpose of this model philosophy was the risk mitigation, with the use of a STM, which helps reducing thermal uncertainties in an early stage of the project, in view of the Instrument CDR.

The verification was made at Bern University in the CHEOPS Thermal Vacuum chamber (shown behind the Instrument, in Figure 21 Error! Reference source not found.), built on purpose for the project. Thermal shrouds can be cooled down to -85°C and cover the whole chamber. Moreover, the facility includes a black painted thermal panel
(passively cooled by radiating coupling with the chamber thermal shroud, controlled with heaters) on top of the Instrument and a liquid nitrogen cooled panel in front of the Instrument FPM radiators to simulate the cold space. For the hot cases, the perturbations of the FPM and the Telescope, due to the environmental variations (change of Earth field of view, albedo flux and Earth Infrared flux), were simulated by the means of the survival heaters with an appropriate voltage tuning.

![Figure 21: CHEOPS Instrument in front of the Thermal Vacuum Chamber](image)

**Figure 21: CHEOPS Instrument in front of the Thermal Vacuum Chamber**

![Figure 22: Instrument inside the Thermal Vacuum Chamber](image)

**Figure 22: Instrument inside the Thermal Vacuum Chamber**

B. Thermal test objectives

- **Instrument STM Thermal Vacuum Test**
  The objectives of the Instrument STM Thermal Vacuum Test were:
  - to show the structural integrity of the Instrument under thermal loads and vacuum,
  - to verify the Instrument thermal design related to the main thermal paths (e.g. FPM – radiators), through the use of dummy heaters in place of the real units,
  - to provide preliminary data for the correlation of the Instrument TMM,
  - to qualify the overall thermal behaviour, including needed heating power and passive temperatures to assess the thermal margins

- **Instrument PFM with FPM-EQM**
  The objectives of the Instrument PFM with FPM-EQM Thermal Vacuum Test were:
  - to show the structural integrity of the Instrument under thermal loads and vacuum,
  - to verify the Instrument thermal design,
  - to provide proper data for the correlation of the Instrument TMM,
  - to show the Instrument functionality within the test temperature range,
  - to formally qualify the Optical Telescope Assembly

- **Full Instrument Proto-Flight Model (PFM)**
  The objectives of the full Instrument Proto-Flight Model (PFM) were:
  - To complete the acceptance test of the Instrument electronic boxes (BEE and SEM) alongside with the acceptance test of the Focal Plane Module Flight Model, which was integrated in January 2018
  - To perform Units Abbreviated Functional Test.
  - To verify the good functioning of survival and annealing heaters.
  - To check The Telescope PID coefficient under perturbation.
  - To perform a final measurement of the Telescope heating power.
  - To check the good functioning of the repaired survival thermistors.

**Figure 23** presents two pictures of CHEOPS Instrument PFM before TV chamber closure
Figure 23. CHEOPS Instrument PFM before TV chamber closure

C. Correlation of the Instrument Thermal Model for the PFM (FPM EQM) Thermal Balance (TB)

Five thermal cases were used to correlate the Instrument thermal model with the test results:
1. Survival case
2. Science cold case
3. FPM step response case
4. Science hot case
5. Science hot case perturbed

Table 5. CHEOPS Instruments TB cases

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<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>1st Case: Survival</td>
<td>~ -30°C</td>
<td></td>
<td></td>
<td></td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2nd Case: Science cold case</td>
<td>~ -20°C</td>
<td></td>
<td></td>
<td></td>
<td>ON - stabilised</td>
<td></td>
</tr>
<tr>
<td>3rd Case: FPM step response</td>
<td>~ -80°C</td>
<td>~ -190°C</td>
<td></td>
<td>Not controlled (passively cooled with the shrouds)</td>
<td>ON – FPM full heating</td>
<td>OFF</td>
</tr>
<tr>
<td>4th Case: Science hot case</td>
<td>~ +45°C</td>
<td></td>
<td></td>
<td></td>
<td>ON - stabilised</td>
<td></td>
</tr>
<tr>
<td>5th Case: Science hot case perturbed</td>
<td>~ +45°C</td>
<td></td>
<td></td>
<td></td>
<td>ON – stabilised Used to simulate orbital loads</td>
<td></td>
</tr>
</tbody>
</table>

The Thermal Panel was used for the 4th and 5th case. The Liquid Nitrogen panel was always at the minimum possible temperature. The 5th case was not a stabilized case. The units were subjected to cycling heat loads for the simulation of the orbital environment by means of the survival heaters. Based on the predicted orbital heat loads (orbit duration 1.63 hour), the FPA capacitor was loaded with a step of 8W for the last 30 minutes, the FEE capacitor with 5.4W and the Telescope tube with 4W.

The TMM of the test set-up was built (as illustrated in Figure 24), with an overall number of thermal nodes equal to 1539. The correlation was performed by solving first the biggest temperature discrepancies, then working out the smaller ones.
At the beginning, the average deviation between test measurements and analysis temperatures was equal to -4.8°C for the 3rd case (with the minus sign indicating a colder temperature for the test) and a maximum standard deviation of 9.4°C for the 4th case.

It was necessary to add some details to the FPM thermal model, like the GMM of the harness, to match the same FEE heating power of the test. The coefficients of the MLI were also tuned to match the same test temperature, which were found to be slightly colder. Large MLI thermal couplings, initially modelled with a combination of a linear coefficient (0.014 W/m²/K) and a radiative coefficient (ε* = 0.019) were finally multiplied by a factor 2. Small MLI couplings (initially using a combined linear (0.036 W/m²/K) and radiative coefficient (ε* = 0.032) were also multiplied by 2 (and even 2.5 around the OB). The emissivity of some coatings was slightly modified: alodine emissivity (initially assumed at ε=0.1) was changed to 0.3. VDA (initially assumed at ε=0.035) was changed to 0.10. This allowed to take into account the small gaps, some cables or some screws which are part of these surfaces. At the end of the process the average temperature deviation was reduced to 1.20°C, while the standard deviation to 2.9°C.

For the Science Cold Case, the heating power of the FPA was equal to 3.9W by analysis vs 3.8 W by test, while the heating power of the FEE was equal to 7.8 by test vs 7.2W by analysis. Due to an issue with the housekeeping of the BEE unit, unfortunately it was not possible to retrieve a reliable duty cycle of the Telescope operational heaters during this test and so to have a reliable measure of the Telescope heating power. This gap will be covered in the frame of the Instrument calibration campaign that is foreseen end of March 2018.

The ability of the units to satisfy the strict thermal stability requirements was demonstrated during the 5th case (Science Hot Case perturbed) above described. The CCD showed a stability of 1.735 mK (rms) @ -40°C despite the induced perturbations. The FEE showed a stability of 0.983 mK (rms) @ -10°C, while the Telescope showed a stability of 136 mK (rms) @ -10°C.

### VII. Overview of the Instrument Final Flight Thermal Predictions

CHEOPS Instrument flight thermal model (as presented in Figure 25) was updated according to the findings of the thermal test campaign. The flight thermal analysis have been updated and confirmed all the Instrument units were in their operational temperature range. The following table shows the predicted Instrument heating power budget for the Science Cold Case, which takes into account the uncertainties found at the end of correlation and which remains in the allocated power budget by the Platform.

<table>
<thead>
<tr>
<th>Thermal Control</th>
<th>FPA</th>
<th>3.38</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 6. CHEOPS Instrument heating power budget in Science Cold Case**

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<table>
<thead>
<tr>
<th>(orbit averages)</th>
<th>FEE</th>
<th>7.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td></td>
<td>19.90</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>30.4 W</td>
</tr>
</tbody>
</table>

Figure 25. CHEOPS Instrument flight model (open cover on the left, close cover on the right)

VIII. Conclusion

CHEOPS Instrument has recently completed its Qualification and Acceptance Review and the predicted thermal performance satisfies the different requirements. The next important step is the delivery Proto-Flight Model and its integration on the Platform, foreseen beginning of spring 2018. The Spacecraft thermal vacuum test is foreseen in July-August 2018, which is in line with the launch readiness by December 2018.

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