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The CHEOPS (CHaracterising ExOPlanet Satellite) mission: telescope optical design, development status and main technical and programmatic challenges

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ABSTRACT

CHEOPS (CHaracterising ExOPlanet Satellite) is the first ESA Small Mission as part of the ESA Cosmic Vision program 2015-2025 and it is planned launch readiness end of 2017.

The mission lead is performed in a partnership between Switzerland, led by the University of Bern, and the European Space Agency with important contributions from Austria, Belgium, France, Germany, Hungary, Italy, Portugal, Spain, Sweden, and the United Kingdom.

The CHEOPS mission will be the first space telescope dedicated to search for exoplanetary transits on bright stars already known to host planets by performing ultrahigh precision photometry on bright stars whose mass has been already estimated through spectroscopic surveys on ground based observations.

The number of exoplanets in the mass range 1-30 MEarth for which both mass and radius are known with a good precision is extremely limited also considering the last two decades of high-precision radial velocity measurement campaigns and the highly successful space missions dedicated to exoplanets transit searches (CoRoT and Kepler).

CHEOPS will be the key instrument to answer the opened questions to improve the measurements precision both mass and radius. The instrument is an optical Ritchey-Chretien telescope configuration with 300 mm clear aperture and a FoV of 0.32° full cone.

As CHEOPS will be in a LEO orbit, straylight suppression is a key point to observe faint stars with very tight stability and straylight rejection. The optical system is designed to image a de-focused PSF of the target star onto the focal plane minimizing stray light using a field stop and baffle system. The telescope will be the only payload on a spacecraft platform providing pointing stability of < 8 arcsec rms. It represents a breakthrough opportunity in furthering our understanding of the formation and evolution of planetary systems.

The main science goal of CHEOPS mission is to study the exoplanets structure with radii ranging from 1 to 6 Earth radii orbiting bright stars. To reach its goals CHEOPS will measure photometric signals with a precision of 20ppm, in 6 hours integration time, on transit measurements of G5 dwarf stars with V-band magnitudes in the range 6<V<9 mag. This corresponds to a signal to noise of 5 for a transit of an Earth-sized planet orbiting a solar-sized star (0.9 solar radii) [1]. This precision will be achieved by using a single frame-transfer backside illuminated CCD detector cooled to 233K (-40C) and stabilized within ~10 mK.

CHEOPS will also provide precision radii for newly discovered planets by the next generation ground-based transits surveys (Neptune-size and smaller) with a photometric precision of 85 ppm in 3 hours integration time of Neptune-size planets transiting K-type dwarf stars with V-band magnitudes as faint as V=12 mag.

This paper shows the main features of the optical design, development status and main technical and programmatic challenges of the CHEOPS instrument. The tight schedule and budget constraints are extremely challenging for the success of CHEOPS that represents the pathfinder and the key for the continuation of the small class science missions in the ESA Science Programme.

I. INSTRUMENT DESIGN

The CHEOPS instrument is a classical photometer measuring variations of light to a very high accuracy. The instrument is split up into four different units on the spacecraft of which two are mounted inside the spacecraft body and two on the outside. The four units are shortly summarized hereafter:

- **The Optical Telescope Assembly (OTA)** includes the structure carrying the telescope, the Back End Optics (BEO), the Focal Plane Module (FPM) and the Radiators. In order to minimize the impact of thermo-elastic deformations on the instrument pointing, the optical heads of the platform star trackers are mounted on the instrument, in proximity of the isostatic mounts of the instrument.
- **The Baffle and Cover Assembly (BCA)** minimizes the stray-light reaching the detector for performance reasons and includes a protective, one shot, cover that protects the instrument from contamination during S/C AIT and launch campaign. The baffle design is implemented similar to CoRoT [3].

- **The Sensor Electronics Module (SEM)** is commanding and controlling the focal plane module that operates the CCD. The SEM itself is controlled by the BEE.
- **The Back End Electronics (BEE)** is the main interface to the spacecraft in terms of power and data transmission. It comprises as well the main instrument computer and power conditioner.

The OTA and BCA together form the CHEOPS telescope, which is mounted onto the top panel of the spacecraft. Fig. 1. shows an artist's impression of the CHEOPS spacecraft assembly. The image looks down the tube of the BCA, which extends the telescope assembly OTA behind. The radiators that are needed for the thermal control of the CCD and proximity electronics are shown on the top. The grey disc to the left shows the BCA one-shot cover in open configuration.

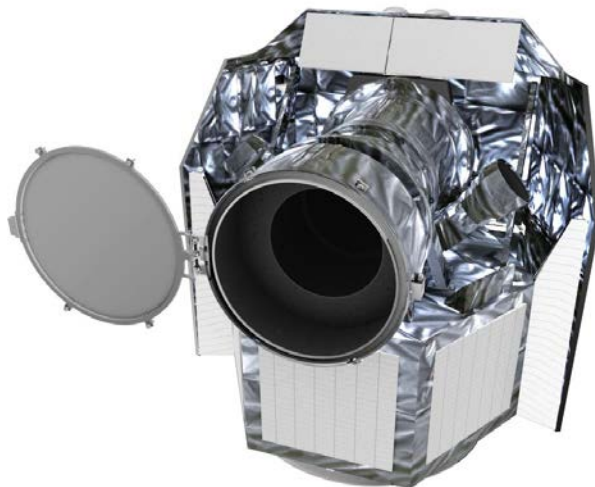


Fig. 1. Artist's impression of the CHEOPS spacecraft (©ESA).

Fig. 2. illustrates the instrument units in more detail. On the top left of the figure, a cut through the CAM/CAD model of the OTA and BCA is shown where the primary and secondary mirror as well as the back end optics (BEO) and the focal plane module (FPM) is illustrated. The two electronics boxes used to control the instrument are shown on the right hand side of the figure.

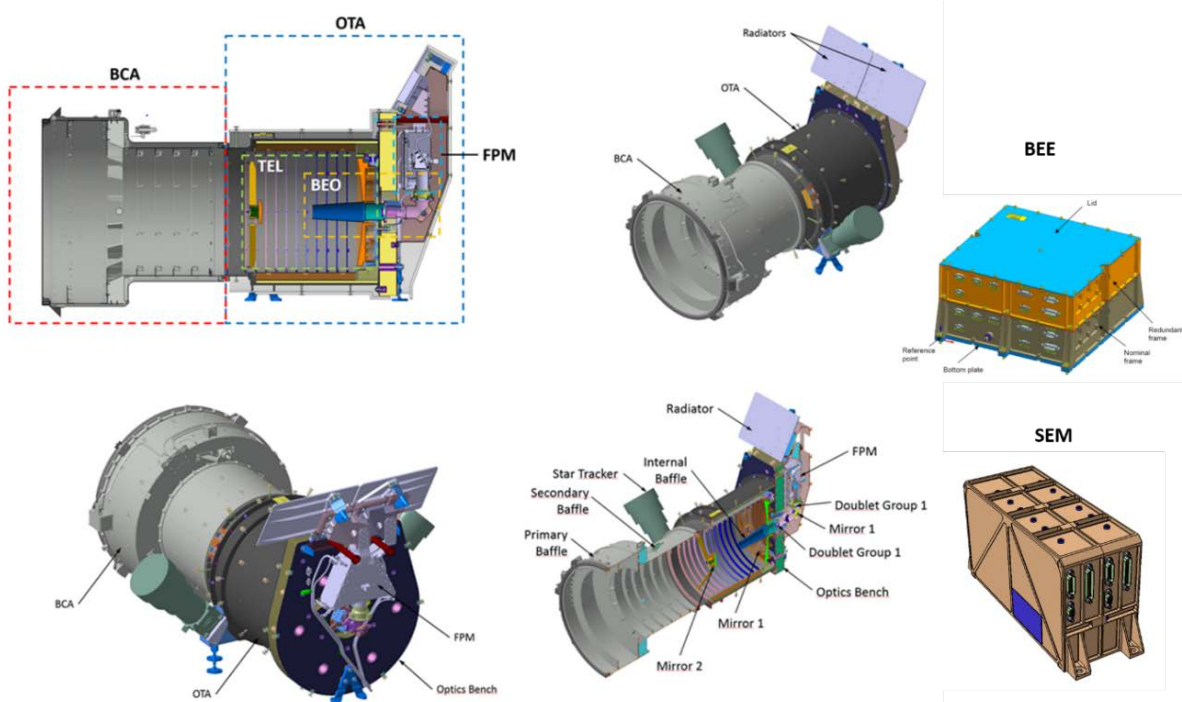


Fig. 2. CHEOPS instrument configuration overview. The four units, the OTA, BCA, BEE and SEM are shown.

The CHEOPS instrument uses a Ritchey-Chretien optical configuration with a BEO to re-imagine the light onto a CCD detector run in AIMO mode. The detector, which was selected for CHEOPS, is an e2v CCD47-20 (13- μ m pixel $1k \times 1k$, AIMO). The CCD is nominally operated at low temperature, 233K, and stabilized to 10mK. This is achieved using a passive cooling system with a dedicated radiator and heaters close to the CCD to reach the relative stabilization.

The entrance pupil of the system is formed by the primary mirror and has a diameter of 320mm. With the central obscuration of the primary mirror, the effective collecting area of the system is 76793 mm². The size of the system have been mainly restricted by the allocated volume inside the fairing. The telescope effective focal length is 1600 mm, giving a telescope focal ratio F/5. The 0.32 degrees field of view is translating into a 1 arcsec/px plate scale on the detector.

The system is using a defocused stellar point spread function (PSF) in order to enhance the photometric performance. A PSF radius of 12 ± 0.7 pixels is currently specified on the detector. The number was a trade off between the flat field performances and the AOCS performance estimations of the S/C. The spacecraft prime contractor, AIRBUS DS Spain, has been in charge of the AOCS performance estimations and the flat field of the CCD is measured at the University of Geneva. The combination of the data resulted in the optimization of the PSF size. The system was designed to have a certain degree of freedom with the alignment of the focal plane module.

As the satellite is in LEO, the stray light reduction of the system had to be addressed carefully. The baffling system, comprising the BCA and the telescope itself, is therefore used to suppress stray light up to a factor of 10^{-12} for higher incidence angles. It is designed to limit the amount of stray light already for sources more than 35° from the optical axis.

Fig. 3. illustrates the CHEOPS optical system with the baffling system on the left hand side and the telescope assembly on the right.

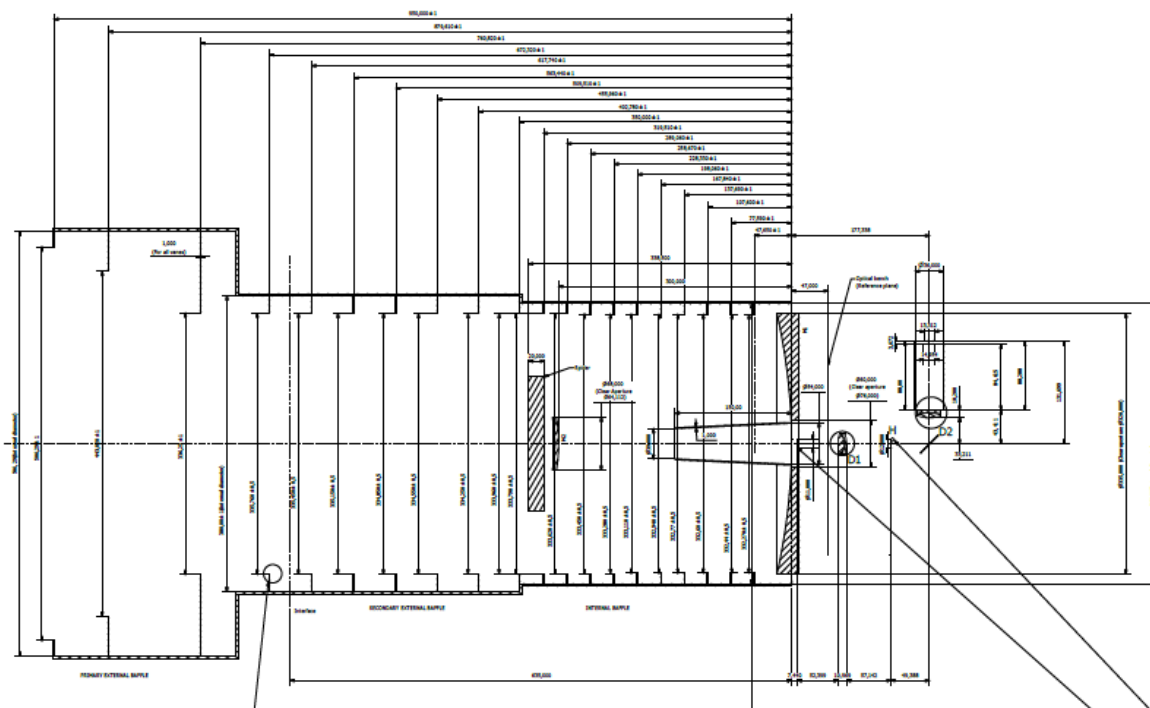


Fig. 3. CHEOPS instrument optical design including the baffling system

In order to have an impression of the BCA and OTA configuration of the instrument, Fig. 4. shows a picture of the structural and thermal model (STM) which has been tested at the University of Bern.

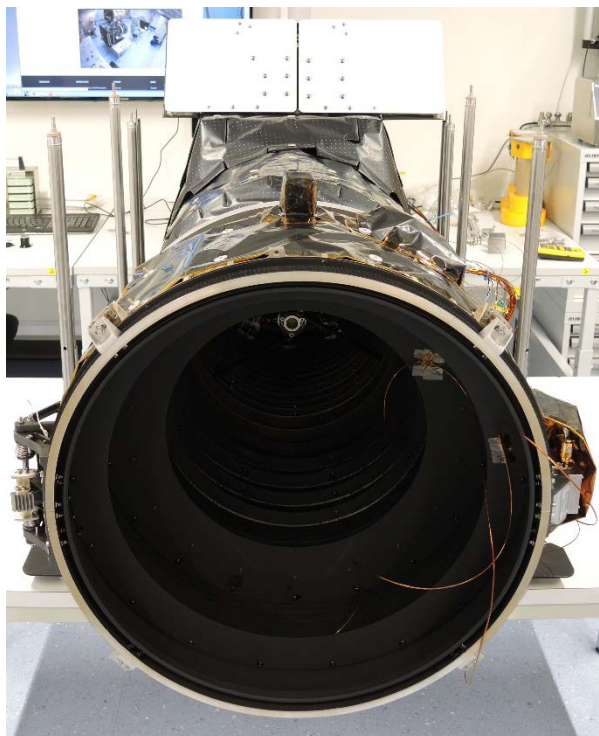


Fig. 4. Picture of the structural thermal model of the BCA and OTA seen from the front side.

The electrical design of the instrument is based on a distributed architecture. The camera system, which consists of the Focal Plane Module (FPM) and the Sensor Electronics Module (SEM), is designed and built by DLR Berlin while the Back End Electronics (BEE) is realized by IWF Graz.

The camera is controlled by the instrument main computer, the BEE, using a SpW link for high data transmission capability. In addition to the data link and software control, the Back End Electronics delivers highly stabilized voltage lines to the SEM in order to ensure the bias voltages stabilities for the camera. This is one of the key drivers to meet the very low noise and high gain stability requirements of the instrument.

The BEE on the other hand interfaces the spacecraft, which provides a redundant power and communication interface.

The instrument is a fully cold redundant system with the exception of the CCD and the CCD clock driver.

II. DEVELOPMENT STATUS

Since the mission adoption in February 2014, considerable progress has been achieved by the CHEOPS team from the consortium and the European Space Agency. The detailed design phase has been concluded, the preliminary design review (PDR) mid 2014 as well as the critical design review (CDR) end of 2015 have been successfully passed. As part of these reviews the interfaces to the spacecraft as well as the system and sub-system specifications were frozen.

Form a hardware perspective, several qualification and interface verification models have been built and tested. A structural and thermal model (STM) of the instrument was realized in 2015. The STM underwent mechanical and thermal qualification before being integrated into the spacecraft mechanical qualification model. Fig. 5. shows a picture of the instrument integration at the ISO5 clean room of the University of Bern and the fully assembled spacecraft mechanical qualification model being ready for sine testing.

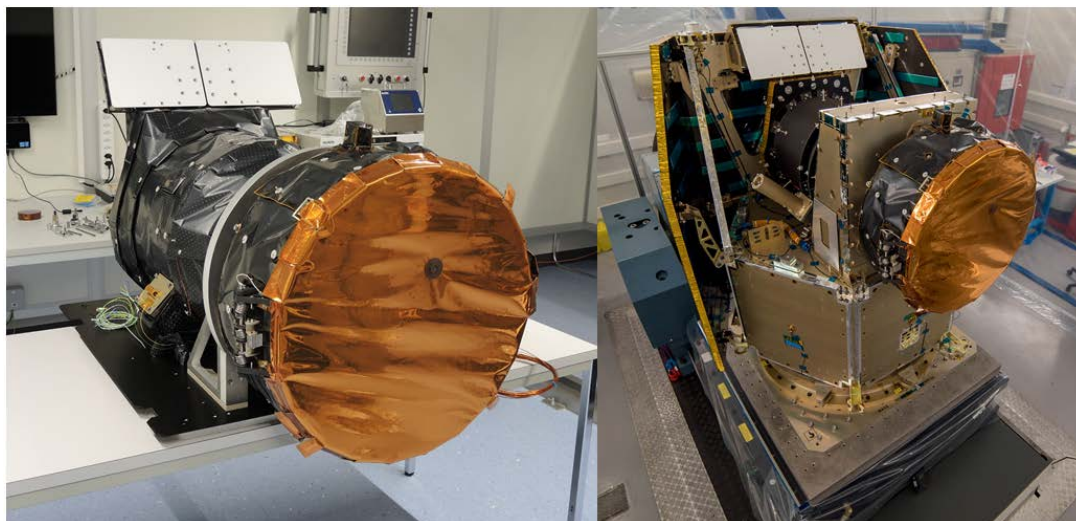


Fig. 5. Pictures of the CHEOPS instrument on the left (University of Bern) and the instrument integrated onto the satellite on the right (Courtesy of Airbus DS Spain)

The spacecraft underwent sine vibration testing, acoustic testing and shock testing. At the end of the test campaign, the verification of the Cover Assembly of the instrument has been performed in order to verify that the launch lock mechanism performs after the environmental loads.

Additionally to the STM tests, a dedicated test campaign has been conducted in order to verify the thermo-elastic performance of the instrument. The dedicated model of the OTA, which consists mainly of CFRP and a honeycomb sandwich optical bench, has been used for the tests. The performance tests were conducted at TNO in Delft [4] and showed that the tight thermo-elastic requirements can be fulfilled. The structure has consequently been refurbished and is used as flight model.

In order to verify the electrical and software interfaces between the SEM/FPM and BEE as well as the interfaces towards the spacecraft, an instrument Electrical Model (EM) was built and tested. The tests were again performed at various stages (unit, instrument and spacecraft). The software used for the camera system, the SEM, is close very close to the flight software as the system is a reuse of the BepiColombo MERTIS camera from DLR [2]. The software on the BEE which is the main interface to the spacecraft provides all the expected telemetry as a heartbeat report, HK data, AOCS centroid report, other asynchronous reports and CCD images allowing testing and validating SW interfaces. Internal algorithms which include centroiding, compression as well as various other engineering algorithms have not been tested at spacecraft level because of time constraints. The EM model however is currently used for further software development at the University of Vienna in order to provide a representative hardware environment.

In order to verify and de-risk the AIV procedures for the telescope optics, a dedicated Demonstration Model (DM) has been realized which was a collaboration between the University of Bern and the Italian industrial Prime LEONARDO. The DM model verification process took place at INAF in Padova and is currently being concluded successfully [5].

For the BEE, SEM and FPM qualification models are realized in advance of the flight models. The BEE box has undergone the full qualification (mechanical, thermal, performance, EMC) already successfully at the Ruag Space in Vienna and IWF in Graz. The SEM and FPM qualification models are currently being integrated and qualified. A very important milestone for the camera system is the performance verification in thermal vacuum, which will be concluded this year.

In view of the flight model or proto flight models substantial progress was achieved as well. The CCD has been procured by ESA, built and tested by e2v. The device has been extensively tested in view of bias level, read out noise, dark signal, gain, non-linearity, PRNU, flat field and quantum efficiency by the Observatory of Geneva. These measurements serve as input to the performance verifications as well as calibration data for operations [6]. The flight models of the Baffle and Cover assembly as well as the telescope structure have been built and qualified for flight already as well. The optics, which are manufactured and integrated by LEONARDO in Florence, are currently under manufacturing and the integration, verification and test of the telescope, is starting still this year. The manufacturing of the flight model electronics, the SEM, FPM and BEE as well is progressing while the testing is scheduled in 2017.

As soon as all individual sub-systems have been successfully manufactured and tested, they are shipped to the University of Bern where the instrument integration and verification will take place. Prior to the integration at

spacecraft level, the instrument will be calibrated as well in Bern with the use of the CHEOPS calibration bench which has been designed, manufactured and tested by the Observatory of Geneva [7].

III. TECHNICAL AND PROGRAMMATIC CHALLENGES

A brief overview is given hereafter concerning the major technical and programmatic challenges, which such an S-Class ESA mission faces in view of the instrument.

The budget and schedule constraints for the ESA S-Class mission have been set very tight. The costs to ESA, who is providing the spacecraft, launcher and parts of the instrument, are cost capped at 50 MEuro while the schedule constraint has been set to 4 years for the development and launch of the mission. Under these constraints, CHEOPS is supposed to deliver top rated science in any area of space science.

The programmatic challenges in view of the tight schedule constraints are obvious. The CHEOPS instrument as well as the spacecraft therefore needed to be a reuse to the largest extent possible. In view of the instrument, this is achieved combining several technologies, which have had flight heritage already. The major drawback is that the instrument consortium and different contributions have been growing as consequence and are more difficult to manage.

In order to mitigate the schedule constraints, clearly defined and stable interfaces needed to be established early in the project. This of course is conceptually doable but still special attention needed to be paid in order to avoid changes. As well, special attention had to be paid in order to specify and maintain the stability of the requirements in order to avoid modifications.

On the technical side, several topics need attention in order to meet the very demanding photometric accuracy requirements. The major topics are briefly summarized hereafter:

- **Straylight suppression**

Depending on the brightness of the observed target, the stray light contribution in the noise budget can have a significant effect. In the case of high stellar magnitude, very dark stars, the stray light, which is due to the Earth albedo, becomes the major part of the photometric error. Therefore the selection of the coatings, the baffle geometries as well as the surface finishes have been a major issue.

- **Cleanliness standards**

The levels of stray light contamination depends on a large degree of the cleanliness level of the instrument, especially the primary mirror. Stringent measures are taken in order to avoid such problems. The requirement imposed to the telescope assembly and the baffle is very tight. Upon delivery of the instrument to the spacecraft provider is set to 200ppm on all internal surfaces. This results in dedicated cleaning procedures as well as working in ISO5 clean rooms, which poses substantial additional work for the entire project.

- **Pointing accuracy**

A high relative pointing accuracy of the entire satellite over a measurement time of typically 48 hours is mandatory. Depending on the flat field precision and the gain stability between different pixels, the smearing effect caused by the spacecraft jitter can degrade the photometric precision of the instrument. Several measures have been taken in order to maximize the pointing accuracy. First, the star trackers of the spacecraft have been placed on the instrument itself to reduce the thermo-elastic deformation between them and the LoS of the instrument. Secondly a payload feedback loop to the AOCS is established to use the high accuracy measurements of the instrument for the pointing accuracy. Thirdly, the PSF size has been optimized in order to reduce the photometric noise.

- **Thermo-elastic stability**

In order to optimize the thermo-elastic stability of the instrument, dedicated CFRP layups in the telescope structure have been developed to meet the very stringent requirements. Additionally dedicated telescope temperature stabilization have been implemented using insulations and large heater patches. Combining the two measures very high stability in the sub-micron range over 30cm distance of M1 and M2 has been reached. This ensures that the noise contribution due to thermo-elastic deformation of the telescope is negligible.

- **Detector and read out electronics temperature stability**

The focal plane module that is hosting the CCD detector as well as the read out electronics requires very strict temperature stabilization in order to meet the photometric performance. The absolute temperatures of 233K for the detector and 283K for the read out electronics are achieved by using the instrument

radiators, which are radiating the excess heat into space. However, more important than the absolute temperature is the temperature stability. For the CCD, the system gain sensitivity was measured to be in the range of 1-2 ppm/mK. In order to minimize the error in the photometric noise the temperature stability requirement is set to 10mK. The temperature stability requirement of the read out electronics is set to 50mK as well to reduce the read out noise. The temperature stability is achieved using dedicated heaters that are PWM controlled in order to heat against the radiators. Additional thermal capacity of the thermal conductor chain to the radiators is lowering the temperature variations as well.

- **CCD bias voltage supply stability**

The stability of the CCD bias voltages supply to the focal plane module as well is a major challenge. The instrument is supplied from the spacecraft with an unregulated voltage that, depending on the battery and the solar cells, can vary. Prior to the SEM, the unregulated power is conditioned in the BEE. The nominal voltage tolerance as well as the voltage accuracy during an observation is key to ensure the proper performance of the camera. The nominal voltage to be supplied from the BEE to the SEM needs to be provided within less than 1% accuracy while the static accuracy is more stringent with less than 0.1% for most of the bias voltages.

Within the SEM and FPM the bias voltages are being conditioned further using linear regulators. As mostly the gain sensitivity of the CCD can introduce noise in the range of tens of ppm/mV the goal is to keep the voltage variations as low as possible.

IV. CONCLUSIONS

CHEOPS, the first small class mission (S-class) in ESA's Science Program, is currently in phase C/D. About half time through the development time, the instrument design, development status as well as the major programmatic and technical challenges are detailed in this paper.

After completing the PRR and SRR in 2013, PDR in July 2014, a complete instrument STM was built and successfully tested at instrument and spacecraft level, including a thermo-elastic stability test using the flight model of the telescope structure. The instrument EM has been tested and provided to Airbus DS Spain beginning of April 2016 and is being tested with the spacecraft EFM. An instrument Demonstration Model was built and tested as well in order to verify the telescope AIV.

The instrument CDR as well as the system has been passed successfully 2016.

Several flight model units and sub-units have already been manufactured and successfully tested while initial measurements provide confidence of that the mission meets the science performances.

V. ACKNOWLEDGEMENT

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