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CHEOPS – Status summary of the instrument development

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ABSTRACT

CHEOPS (CHaracterizing ExOPlanets Satellite) is the first ESA Small Mission as part of the ESA Cosmic Vision program 2015-2025. The mission was formally adopted in early February 2014 with a 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 mission is dedicated to searching for exoplanetary transits by performing ultrahigh precision photometry on bright starts already known to host planets whose mass has been already estimated through ground based observations. The instrument is an optical Ritchey-Chretien telescope of 30 cm clear aperture using a single CCD detector. The optical system is designed to image a de-focused PSF onto the focal plane with very stringent stability and straylight rejection requirements providing a FoV of 0.32 degrees full cone.

The system design is adapted to meet the top-level science requirements, which ask for a photometric precision of 20ppm, in 6 hours integration time, on transit measurements of G5 dwarf stars with V-band magnitudes in the range $6 \leq V \leq 9$ mag. Additionally they ask for 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.

Given the demanding schedule and cost constrains, the mission relies mostly on components with flight heritage for the platform as well as for the payload components. Nevertheless, several new developments are integrated into the design as for example the telescope structure and the very low noise, high stability CCD front end electronics.

The instrument and mission have gone through critical design review in fall 2015 / spring 2016. This paper describes the current instrument and mission design with a focus on the instrument. It outlines the technical challenges and selected design implementation. Based on the current status, the instrument noise budget is presented including the current best estimate for instrument performance.

The current instrument design meets the science requirements and mass and power margins are adequate for the current development status.

Keywords: CHEOPS, S-Class, University of Bern, ESA, Instrument, Exoplanets, Photometry, Performance

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1. INTRODUCTION

A large number of exoplanets have been discovered since the discovery if the first planet orbiting a star similar to the Sun was found in 1995 by Mayor and Queloz from the Geneva observatory [1]. The field of exoplanet characterization has in fact evolved in big steps since then.

The two most successful methods rely on detecting dynamical (radial velocity) or photometric (transit) perturbations on the host star induced by the presence of one or several planets. While the first detection method provides a lower limit on the mass of the planet (as performed in [1]), the second one provides an estimate of the radius of the planet. Combining the two methods is of particular interest as for these objects both mass and radius are known. From these values, a mean density can be estimated which allows conclusions on the nature of the planet.

After two highly successful space missions performing transit measurements (CoRoT and Kepler) and almost two decades of high-precision radial velocity measurements, the number of exoplanets in the mass range 1-30 M_Earth for which both mass and radius are known to a good precision, is still limited. The reason for this is that most of the CoRoT and Kepler targets are too faint to be measured accurately enough with current, ground based, Doppler techniques. This means that the overlap of the planets with known masses and known radii is very limited. The major objective of the CHEOPS mission is in fact to significantly increase the sample of objects for which both quantities are known.

CHEOPS has been selected in 2012 and adopted in 2014 as the first S-class mission of the ESA Science Programme. ESA and the SPC have been setting very tight constraints on the mission. Namely the development time from adoption to launch shall not exceed 4 years and the total cost to ESA is restricted to 50 M€. The total cost of the mission is estimated to approximately 150 M€ where the mission consortium covers the rest of the cost. This corresponds to about 10% of the ESA budget of an M-mission and less than half the development time of an M-mission. The continuation of an S-mission line in ESA's Science Programme hinges on the success of CHEOPS.

This paper describes the CHEOPS scientific objectives, the instrument and its development status roughly two years before the envisaged launch.

2. SCIENTIFIC OBJECTIVES

A detailed summary of the scientific requirements and their motivation can be found in the CHEOPS Definition Study Report [2]. Hereafter, two of the scientific requirements are described, which are considered as most important. Namely, they are the photometric accuracy of the measurement and the target observability and sky coverage.

CHEOPS will target several different type of stars known to host planets ranging from 6 to 12 magnitude stars. It will target host starts of super-Earth planets found by ground based radial velocity measurements, Neptune-like planets detected from ground based transit surveys and as well, planets found from space based transit observations like TESS. The photometric accuracy that is required from the entire system is depending on the stellar magnitude. Two different photometric accuracy requirements have been established:

- CHEOPS shall be able to detect Earth-size planets transiting G5 dwarf stars (stellar radius of 0.9 $R_\odot$) with V-band magnitudes in the range $6 \leq V \leq 9$ mag. Since the depth of such transits is 100 parts-per-million (ppm), this requires achieving a photometric precision of 20 ppm (goal: 10 ppm) in 6 hours of integration time. This time corresponds to the transit duration of a planet with a revolution period of 50 days.
- CHEOPS shall be able to detect Neptune-size planets transiting K-type dwarf stars (stellar radius of 0.7 $R_\odot$) with V-band magnitudes as faint as V=12 mag (goal: V=13 mag) with a signal-to-noise ratio of 30. Such transits have depths of 2500 ppm and last for nearly 3 hours, for planets with a revolution period of 13 days. Hence, a photometric precision of 85 ppm is to be obtained in 3 hours of integration time. This time corresponds to the transit duration of a planet with a revolution period of 13 days.

Additionally to the photometric accuracy, one main scientific requirement is considering the sky coverage of the mission. As CHEOPS is a follow up mission, it is essential to its success to be able to observe as much of the sky as possible where previous planets have been found. A large fraction of the targets, which will be observed are planets discovered using Doppler velocimetry, which are essentially ground based observations. This is in line with the objective to evaluate the planet's mean density. The requirements, which have therefore been derived, are the following:

- 50% of the whole sky shall be accessible for 50 (goal: 60) cumulative (goal: consecutive) days per year and per target with time spent on-target and integrating the target flux longer than 50% of the spacecraft orbit duration (e.g., >50 min for a 100-min spacecraft orbital period).

- 25% of the whole sky, with 2/3 in the southern hemisphere, shall be accessible for 13 days (cumulative; goal: 15 days) per year and per target, with time spent on-target and integrating the target flux longer than 80% of the spacecraft orbit duration (>80 min for 100-min spacecraft orbit).

The sky coverage requirements are taken into account at mission, platform and instrument level. Other science requirements like target observability, magnitude range of targets, time cycle and lifetime of the mission can be found in [2].

3. CHEOPS INSTRUMENT

The CHEOPS instrument consists of four units, which are mounted to the spacecraft structure, two of them are internally and two externally mounted. The instrument configuration is shown in Figure 1.

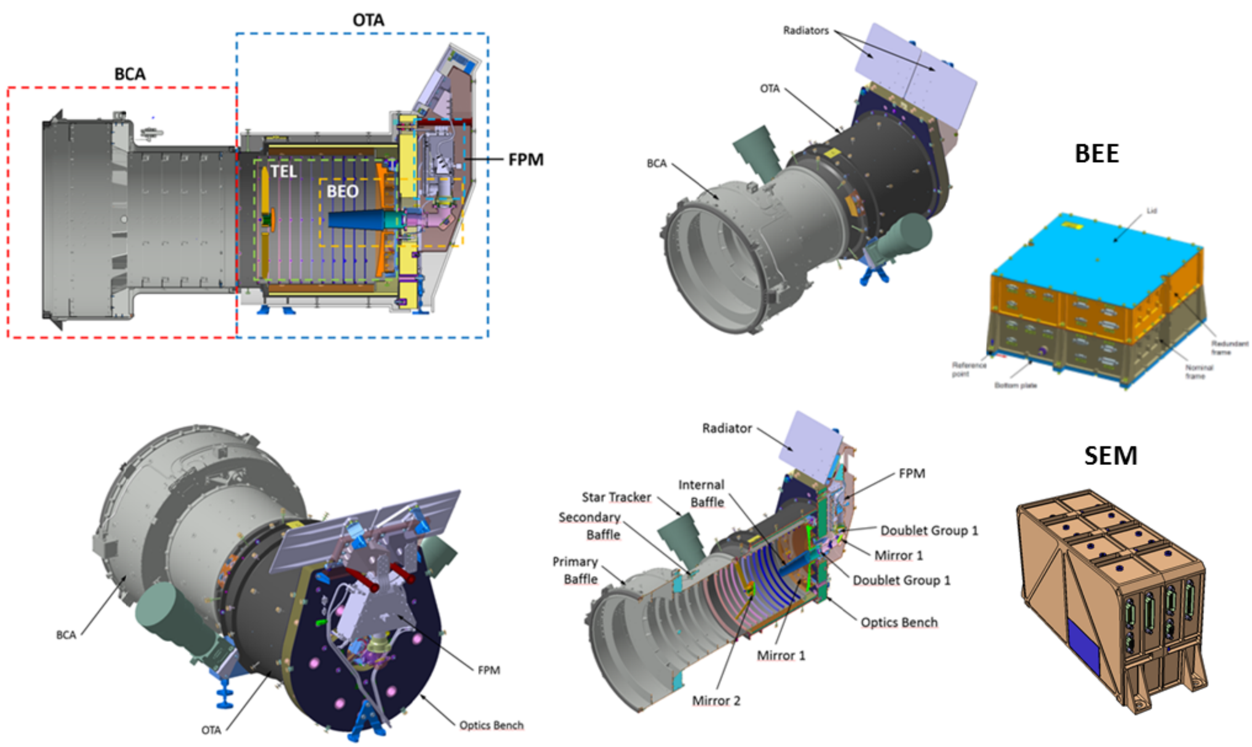

Figure 1: CHEOPS instrument configuration overview. The four units, the OTA, BCA, BEE and SEM are shown.

The instrument 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 OTA, 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 **Sensor Electronics Module (SEM)** is commanding and controlling the FPM that operates the CCD. It 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 CHEOPS instrument is a photometer measuring light variations to a very high accuracy as stated in the chapter above. This is performed using a Ritchey-Chretien optical configuration in the OTA with a BEO to re-imagine the light onto a CCD detector run in AIMO mode. The entrance pupil of the system is located at the primary mirror and has a diameter of 320 mm. Considering the central obscuration of the primary mirror, the effective collecting area of the system is 76793 mm^2. The size of the telescope has been mainly restricted by the allocated volume due to the size of 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.
Figure 2 illustrates the optical setup of the instrument. The baffling system, comprising the BCA and the telescope itself, is 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. This is needed to avoid introducing photometric errors due to varying light hitting the detector.

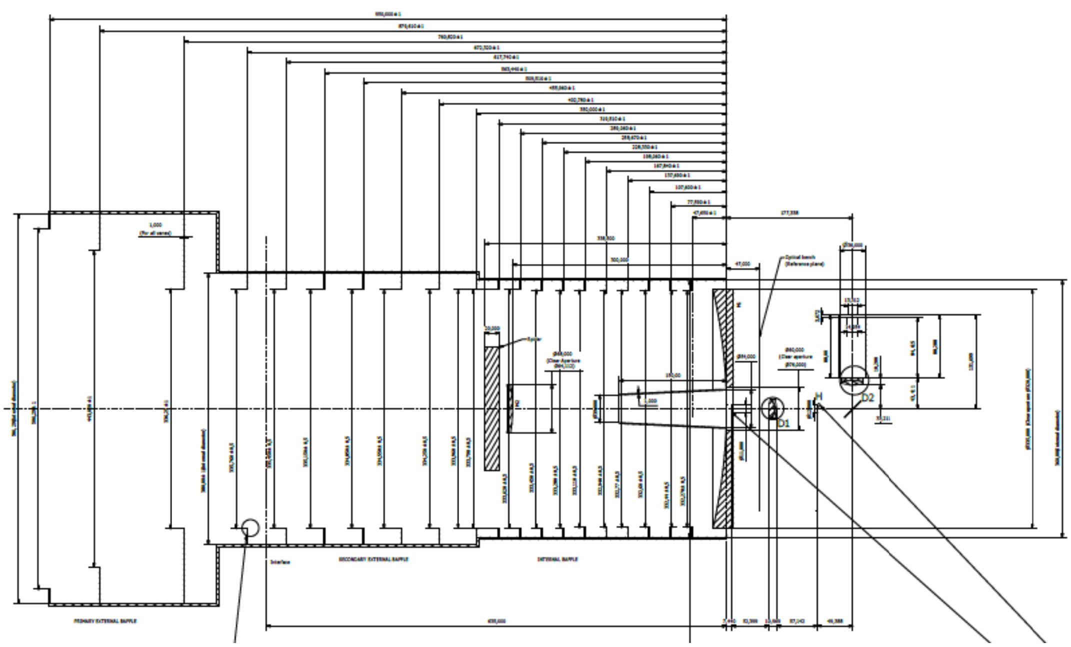

Figure 2: Optical setup of CHEOPS

A picture of the baffle and cover assembly prior to TV testing is shown in Figure 3. This configuration of baffle using a spring-loaded hinge and a Frangibolt actuator has been flown on CoRoT and was adapted mostly in size for the CHEOPS mission. The Centre Spatial de Liège (CSL) in Belgium provides the baffle.

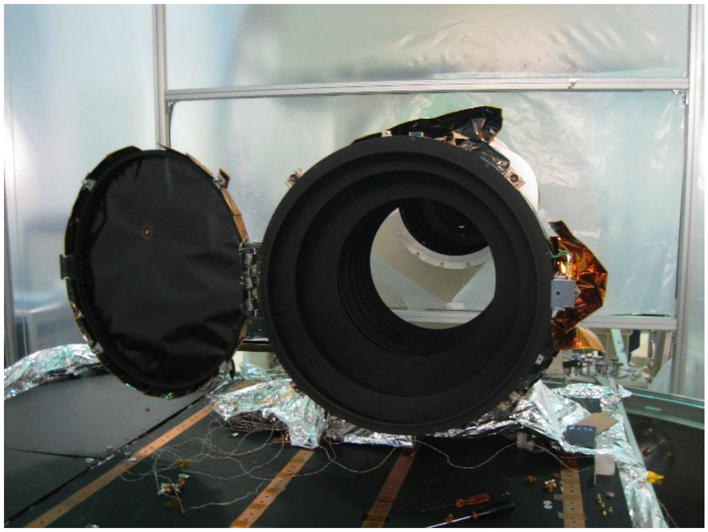

Figure 3: Picture of the baffle and cover assembly before TV testing.

CHEOPS uses a defocussed stellar point spread function (PSF) as well to enhance the performance. This is a trade-off between the pointing jitter introduced by the AOCS pointing performance and the flat field performances.
Figure 4 shows a simulated defocussed point spread function at the detector position. As expected, in the PSF the feature due to the telescope central obstruction and to the Poisson spot can be clearly seen. Effects of mirror trefoil and secondary mirror spider have also been taken into consideration. The trefoil effect is a consequence of the thermo-mechanical deformation of the primary mirror due to the operating temperature of -10°C and the three mechanical mounting points.

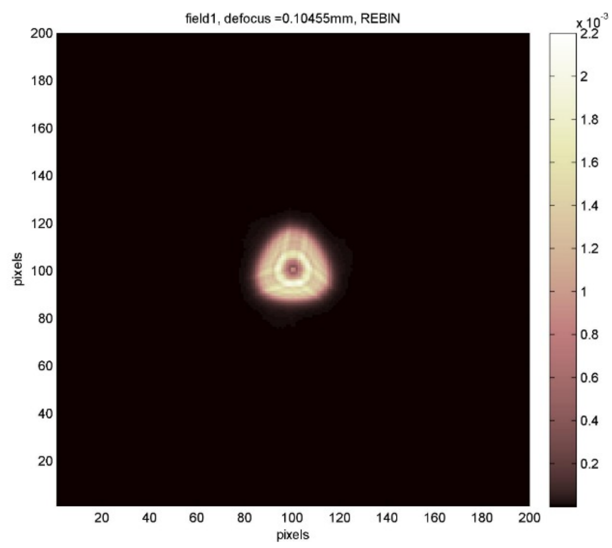

Figure 4: Simulated defocussed point spread function.

The CHEOPS camera is built as a distributed computer system, which consists of a Back End Electronics, the BEE, and the Sensor Electronics System, the SEM, which is controlling the CCD and the proximity electronics. This is mainly a result of the mission constraint on the schedule. Space flight heritage has been used for both units. The camera itself, the SEM and the FPM, is to a large part a re-use of the Mertis camera used in the BepiColombo mission [4].

The detector selected for the mission and integrated into the focal plane is an e2v CCD47-20 (13-µm pixel 1k × 1k, AIMO). The CCD is nominally operated at low temperature, 233K, and is passively cooled by a dedicated radiator. The radiator used to cool the CCD can be seen in Figure 1 and is the left one when viewed from the telescope aperture.
Figure 5 shows in the left picture a detailed CAM/CAD view of the SEM and FPM. On the right picture, the internal design of the focal plane model can be seen with the CCD detector in the center of the image. The picture shows the qualification model of the module at an early integration stage at DLR Berlin premises.

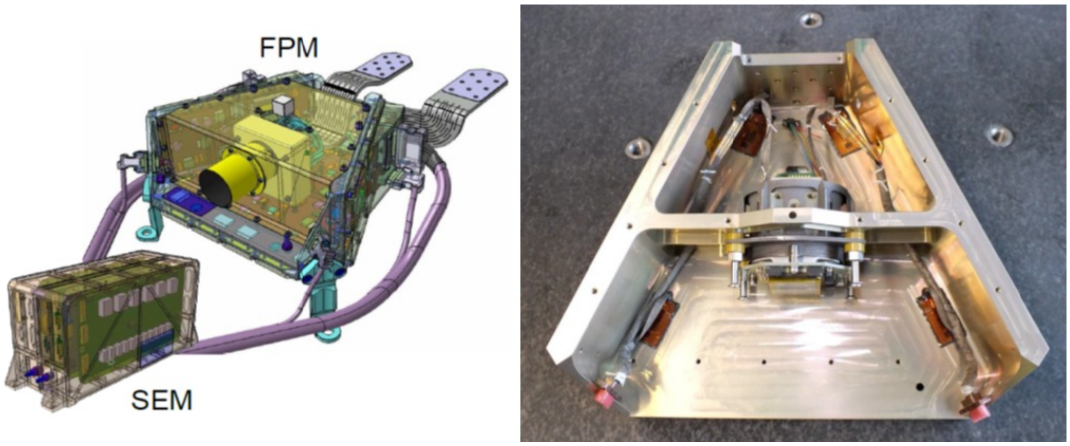

Figure 5: SEM and FPM CAD view (left) and FPM EQM model (right) at DLR Berlin.

The FPM-SEM architecture is mainly driven by the thermal design having 3 different categories reflecting the requirements of thermal control:

1. Focal Plane Assembly with CCD and proximity electronics operating at lower than 233K nominally stabilized by heating against a dedicated radiator.
2. Front End Electronics (FEE) with analogue and CCD low level control electronics operating between 253– 283 K stabilized by heating against a dedicated radiator.
3. Sensor Controller Unit and Power Conditioning Unit (SCU & PCU), including FPGA – based digital electronics for data handling and controlling the CCD detector by different readout modes at standard temperatures without stabilization needs.

Due to the sensitivity of signals and clocks against cross talk and disturbances, the analogue electronics according 1 and 2 is organized in close vicinity.
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 Data Processing Unit (DPU) hardware is based on the GR712, which contains two LEON3 processors and provides the space wire interface to the SEM and MIL-1553 interfaces towards the spacecraft. The DPU carries a mass memory to allow for 3 days operation without ground contact. 3D-Plus provides a FLASH memory in the configuration of 4 Gbit times eight bit. For effective operation of the processor, four components are used to provide 32bit access and EDAC.
The configuration foresees the flash memory for storage of telemetry data. In addition, the on-board backup of the application software is stored in this area. To increase the reliability, in particular for the backup of the application software, several copies are located at different pages. Four standard chips are combined to a stack and packed into a common package. Due to this configuration, it is unlikely that one high energetic particle would hit a similar address range on all pages at the same time. The four chips are accessed by individual chip enable, read and write enable signals. The command latch enable and the address latch enable is common for all four chips. The total size of the memory to be used for data is 16 GByte.

Since the average telemetry is 1.2 Gbit/day, the same memory cell will be used approx. three times per year. Therefore the limited life time of the component (~100.000 write cycles) is negligible.
In order to have an overview of how the units are electrically connected Figure 6 can be consulted. The central part of the scheme is showing the spacecraft power, CMD&Data and the analogue interfaces are shown which are connected to the BEE, BCA and instrument survival and annealing heaters. The BEE on the other hand interfaces the SEM and the OTA operational heaters, which are used to maintain a constant telescope temperature.

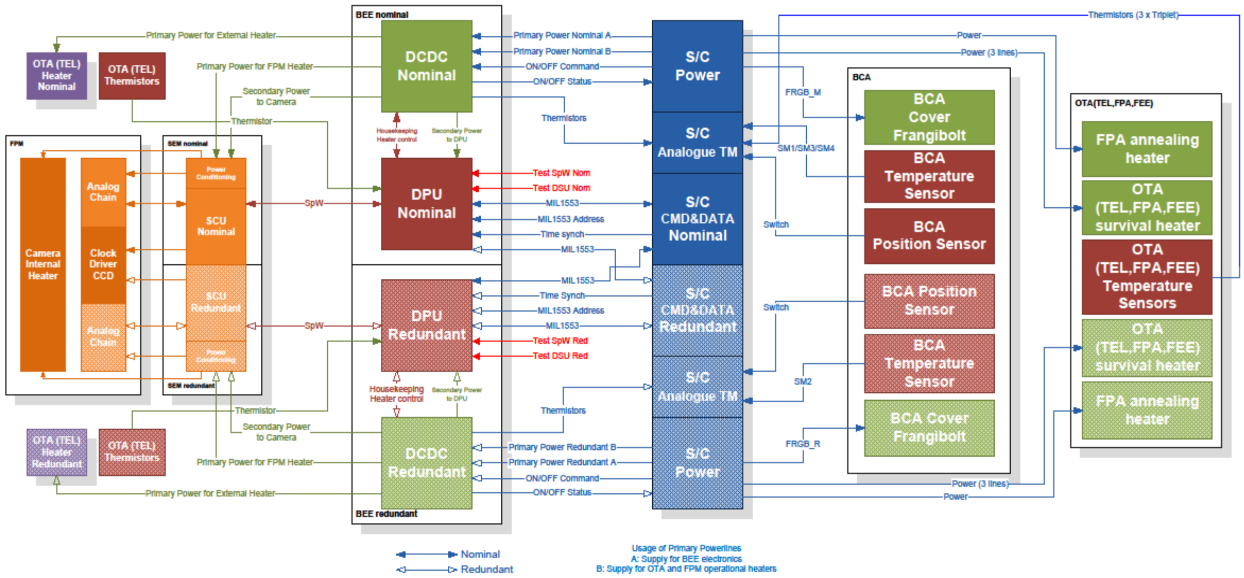

Figure 6: CHEOPS electrical sub-system overview.

The working principle of the instrument is that of a high precision photometer as already mentioned above. There is however one important additional aspect which needed to be considered in the instrument and mission design. Because the spacecraft with its star trackers has a limited relative pointing accuracy, two important measures were taken to improve the design. First, the star trackers have been accommodated on the instrument itself to limit the thermo-elastic distortion between them and the line of sight of the instrument and secondly the spacecraft AOCS operates with the payload in the loop. The instrument therefore is computing the centroid of the target star and its deviation from the desired target location and feeds this information back to the spacecraft for it to correct thermoelastic drift. This improves the pointing accuracy significantly.

4. MAJOR CHALLENGES

This chapter gives a brief overview about the major technical challenges of the CHEOPS instrument development. The programmatic challenges are not discussed here but are mainly focused on the very tight schedule and low budget constraints imposed on the mission. Counter measures to these involve mainly high TRL levels of the sub systems, a dedicated industrial implementation approach, stability of requirements and early and clearly defined and stable interfaces.
Most of the technical challenges are indeed a consequence of the stringent requirements of the photometric stability.
In order to meet the high accuracy photometric requirements mainly the following issues arise to be solved for the CHEOPS instrument:

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.
In order to cope with the stray light, a baffling system similar to the one of CoRoT has been implemented [5]. The internal parts of the baffling systems are all black coated using different coatings depending on the surfaces.

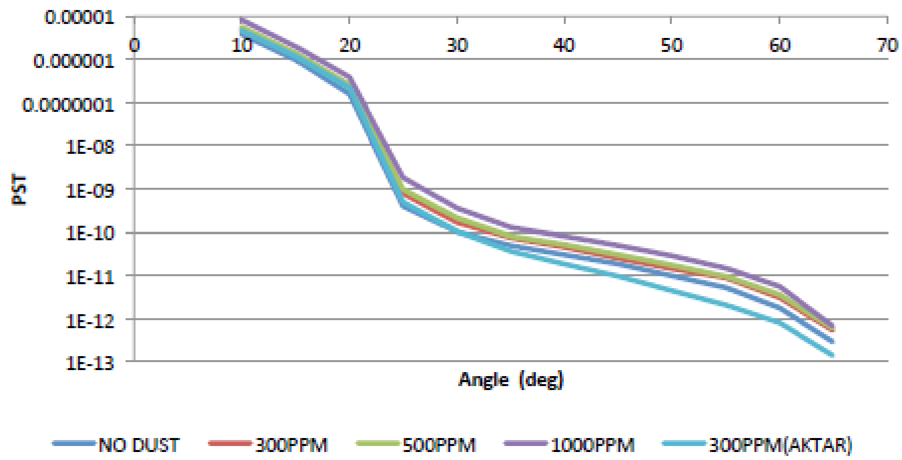

Figure 7: Stray light rejection calculations of the CHEOPS baffling system for different cleanliness levels. In addition, the stray light suppression capability is shown if improved black coating (Aktar) would be used.

Figure 7 illustrates the stray light rejection capabilities of the baffling system as function of the incidence angle for different particulate contamination states of the primary mirror. It is shown that after an incidence angle of 35° with respect to the line of sight the stray light rejection capability reaches a value of less than 10^{-10}. It is however very important to ensure a very low contamination level which leads directly to the next point.

Cleanliness standards

As shown above, the stray light level depends to a large degree of the cleanliness level. Mainly the particulate contamination on the primary mirror leads to unwanted scattering of light, which leads to stray light contamination on the detector. In this case, the light arrives on the detector outside the stellar point spread function which influences directly the photometric precision of the instrument.
Stringent measures are taken in order to avoid such problems. The requirement that is 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. As the capability to clean coated surfaces and mirrors is limited very stringent clean room requirements have been put in place. All the integration and testing of the baffle and telescope assembly is performed in ISO5 clean rooms for all the actors which adds substantial additional work to the project. This needs to be in line with the tight schedule of the mission.

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.
There have been several measures implemented to prevent the dominance of this effect in the noise budget. On the one hand, the spacecraft star trackers have been accommodated directly on the payload in order to limit thermo-elastic

distortions. Thermo-mechanical model analysis indeed show that the on orbit stability between the star tracker interface and the telescope line of sight is less than 3 µrad over one orbit which is almost a factor 100 better than required.
On the other hand, a payload feedback loop to the spacecraft AOCS is implemented. The payload provides the spacecraft with more accurate pointing information which is retrieved from the photometric measurement itself. The instrument calculates a centroid position if the stellar PSF and sends the offset to the nominal position to the spacecraft. This can be performed with sub-arcsecond precision.
Thirdly, the stellar image is defocused spreading the light over 500 pixels which statistically averages the different pixel sensitivities leading to a significant reduction in jitter noise.
Using these measures, the photometric noise introduced by the spacecraft jitter is calculated to be well below 5ppm after several hours of observation which is shown in Figure 8.

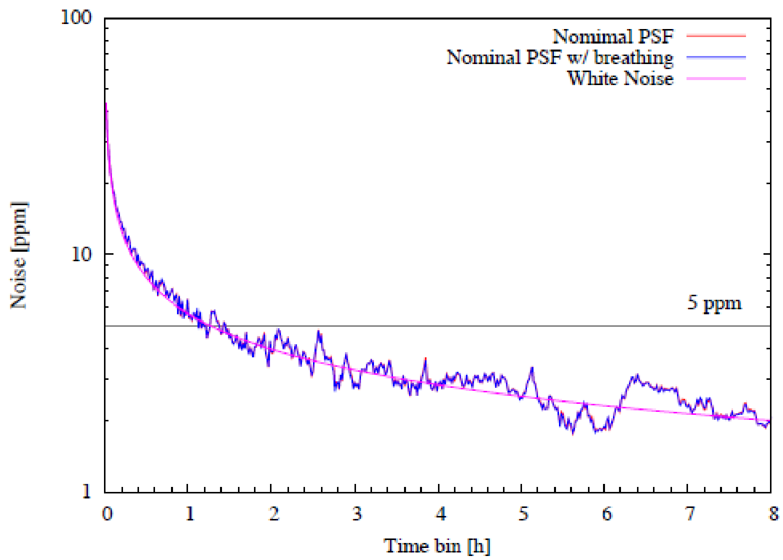

Figure 8: Simulated photometric noise from S/C jitter as a function of integration time. Simulation considering the baseline PSF, the jitter time series scaled by a factor 3 and a normally distributed flat field residuals. The red line shows the noise evolution after binning the images to each time bin. The PSF corresponds to the model where the temperature of the structure is fixed at -10°C. The blue curve considers that the PSF changes due to variations in the temperature of the structure (breathing effect). Due to the extremely stable structure, the breathing is negligible. The magenta curve shows the expected behaviour of a pure white noise, depicted here for comparison.

Thermo-elastic stability

Thermo-elastic stability of the instrument is as well a key point of the development of CHEOPS, which could highly influence the photometric precision. Dedicated optical analysis performed by INAF in Padova using the input of the thermo-elastic models revealed that the highest contributor of the noise potentially introduced by thermo-elastic deformations is the change in distance between the primary and secondary mirror (see Figure 9). This has been called 'thermal breathing' of the telescope.

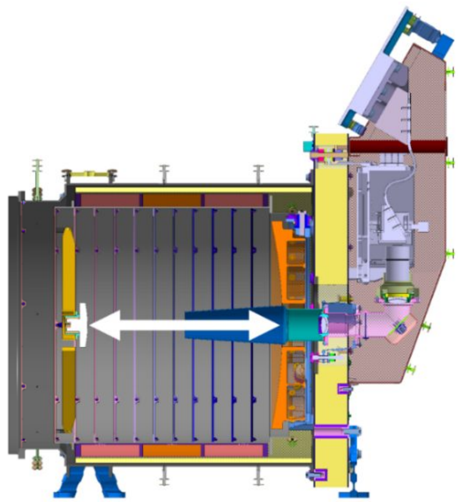

Figure 9: CAD cut view of the telescope with the arrow indicating the distance between primary and secondary mirror.

As well, in this case two measures have been implemented to prevent this problem and reduce the noise contributions from this parameter. First the entire telescope structure has been designed in order to have a minimal CTE over the operational temperature range with focus on the inter mirror distance. Very demanding requirements of 0.75 µm distance variation over a length of 30 cm have been imposed. Thus the CFRP layup has been optimized in this direction. Blecha et. al. is going into the details of the design implementation and verification of the telescope structure in [6] whereas the test setup in described in [7].

Secondly, the temperature stability of the telescope structure itself was optimized. The CFRP telescope tube is indirectly heated by 2+2 heaters (front and back) located on an aluminum structure in order to stabilize the operating temperature. Figure 10 illustrates the setup where the operational heaters, at the two ends of the tube are indicated. The heaters between the operational are used for survival purposes.

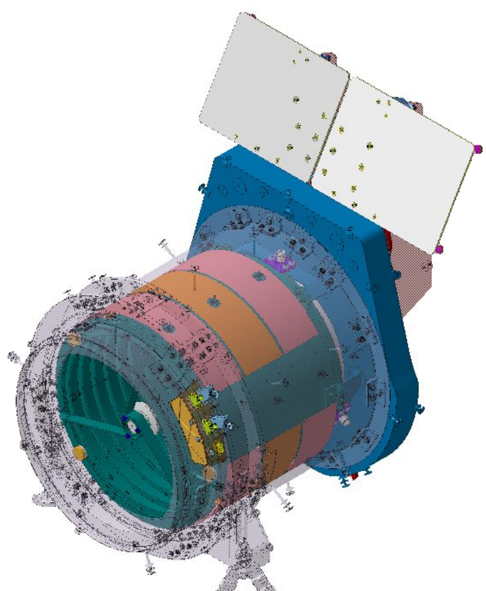

Figure 10: Setup of the telescope operational and survival heaters.

This setup has been tested with the instrument Structural and Thermal Model (STM) in the TV chamber in Bern. The thermal model, which was correlated using these test results, predicts that the temperature stability in orbit is maintained well below one degree Celsius over one orbit.

Combining the two results of the CTE measurements and the thermal model prediction leads to the conclusion that the 'thermal breathing' of the telescope leads to a negligible contribution of the noise budget. The results show that the requirement is maintained with a high margin.

FPM 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 temperature requirement is anticipated in chapter 3. The detector temperature baseline is currently set to 233K. This minimizes the dark noise output of the device as well as the system gain sensitivity. The read out electronics, however, is operated at higher temperature with 283K as a baseline. The absolute temperature of the focal plane parts is ensured by the instrument radiators, which radiate the excess power into space. The focal plane is connected to the radiators using thermal straps.

However, more important than the absolute temperature is the temperature stability. For the CCD, the system gain sensitivity is 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 10 mK. This requirement needs to be fulfilled during one full observation, which lasts typically 48 hours. The temperature stability of the read out electronics and the bias voltage references, which are located in the FPM body, are slightly less stringent. The current assumptions following a stability error analysis lead to the conclusion that a stability of 50 mK needs to be achieved.

The temperature stability of the focal plane module is achieved using dedicated heaters which 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. The stability requirements will be verified by dedicated EQM thermal vacuum tests.

Bias voltage supply stability

In addition to the stability of the CCD bias voltages generation in the focal plane module the supply voltages of the SEM/FPM sub-system needed to be addressed. 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.

Distributed computer architecture

Mainly as a consequence of the mission constraints the architecture of the instrument can be seen as distributed architecture. The camera system consisting of the SEM and FPM are controlled by the main computer and interface to the spacecraft, the BEE. This adds additional complexity to the system as another software and hardware interface is needed. The camera system is providing the CCD pictures as well as the housekeeping data to the BEE where they are processed. Major activities of the instrument main computer are, besides the re-packing of the data, the calculation of the stellar image centroid for the feedback loop towards the AOCS and the compressing of the science data.

Interface tests using the BEE and SEM engineering models have been performed in order to validate the proper performance at an earlier stage of the project.

5. DEVELOPMENT STATUS

Two and a half years after mission adoption considerable progress has been achieved by all parties. 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.
From a hardware perspective the Structural and Thermal Model (STM) has been manufactured and tested on instrument level as well as on spacecraft/system level. Figure 11 shows the BCA and OTA integrated in the ISO5 clean room in Bern. With the thermal hardware (MLI, heaters, thermistors and radiators) installed it underwent thermal balance/cycling tests in the purpose built thermal vacuum chamber. The STM served following purposes at various integration levels:

- Verification and training of the complete integration of the instrument including thermal hardware, BCA-OTA interface and star tracker dummies.
- Thermal balance and thermal vacuum cycling tests at instrument level.
- Mechanical vibration tests for launch load endurance verification.
- Correlation of the thermal and mechanical models to the tests.
- Verification of the mechanical interfaces with the spacecraft.
- Coupled mechanical loads (sine, acoustic and shock) verification campaign at spacecraft level.

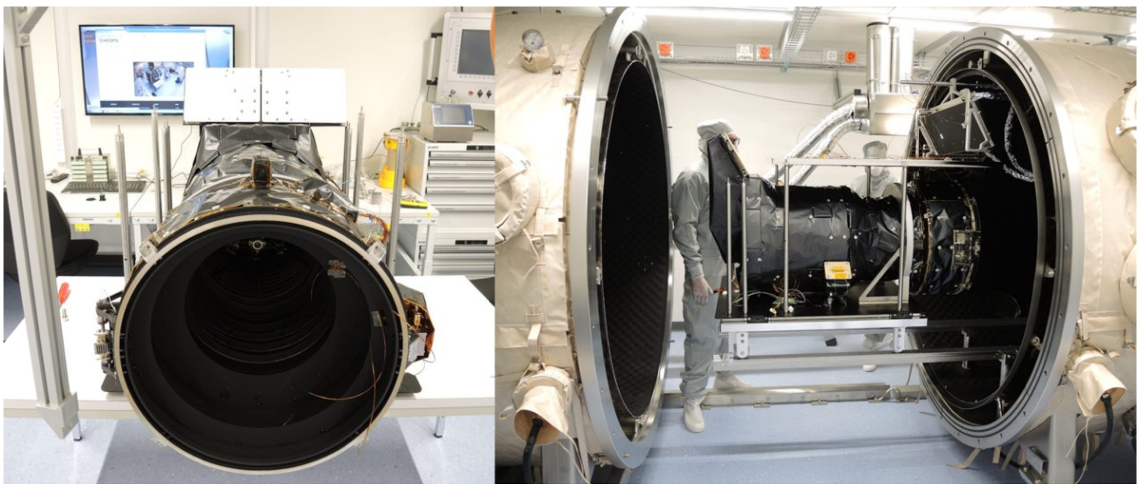

Figure 11: OTA and BCA STM in the clean room in Bern. Left picture shows the view from the aperture while the right picture shows the integration into the TV-chamber.

Figure 12 illustrates the various stages of the spacecraft Structural Qualification Model (SQM) test campaign, which has been conducted by 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.

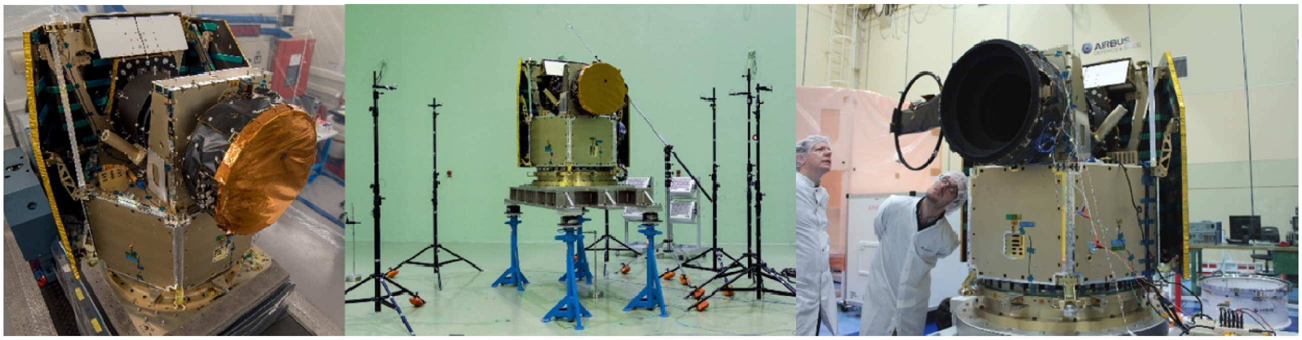

Figure 12: Spacecraft SQM model during sine vibration test (left) at Ruag Space AG, SQM during acoustic test (center) at ESTEC and opening of the cover following mechanical test campaign (right) at ADS (Courtesy of Airbus DS Spain).

The structure of the telescope has been verified for thermo-elastic performance. Chapter 5 addresses this design challenge separately. The flight structure, which was called ‘STM2’ has been used for the tests. The test results have shown that the structure performs exceptionally well. Details can be found in [6]. The ‘STM2’ was refurbished after the thermo-elastic verification campaign and serves as the proto flight model (PFM).

Additionally, an instrument Electrical Model (EM) has been built and tested. The EM is composed of three hardware elements: Back End Electronics Box, Sensor Electronics Module and Focal Plane Module Load Simulator. It includes only one electrical branch and is fully representative of the flight configuration with respect to spacecraft electrical and software interfaces allowing testing and validating interfaces prior to integrate the flight instrument model on system level.

The tests again have been performed at various integration stages. The EM was extensively tested at instrument level in order to verify the internal as well as the external interfaces. The software that is installed on the SEM is close to the flight software as it is to a very high degree a reuse of an existing system. 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. The scientific algorithms, like the centroiding and the compression, as well as various engineering algorithms however have not been implemented for the EM as the time constraints did not allow for it.

Additionally to the instrument STM and EM, a further model was built. The instrument Demonstration Model (DM) consists of an aluminum telescope structure and the optical elements. This model verifies the integration and alignment of the optics into the structure. A dedicated SPIE paper can be found in [8].

In view of the flight units or proto-flight units substantial progress can be reported as well. Several flight units and sub-units are already built and tested.

The flight CCD, which has been procured by ESA, has been built and tested by e2v. After the device testing at e2v the CCD has been transferred to the Geneva Observatory for the very detailed performance testing. The extensive testing has been performed in a cryostat at the CCD’s operational temperature of 233K. The measurements serve as calibration data for the instrument as well as input for the noise and performance estimations briefly shown in the next chapter. Among other tests following were performed:

- Bias level and read-out noise
- Dark signal
    - Variations with the temperature
- System gain
    - Variations with the temperature
    - Variations with the bias voltages
- Non linearity and saturation level
    - Variations with the bias voltages
- Photo-response non-uniformity and flat fields
    - Variations with the wavelength
- Relative quantum efficiency

The flight model of the Baffle and Cover Assembly has been built, mechanically and thermally qualified. Upon delivery a second thermal qualification run is envisaged due to a design flaw which has been found out and fixed in the previous TV qualification. The telescope structure without the optics was as well manufactured and underwent qualification successfully. To complete the telescope, the optical elements are being manufactured and undergo qualification. The integration of the optical elements into the mechanical structure is taking place in the summer 2016. Following the integration, the telescope undergoes performance testing and qualification as well.
For the BEE, SEM and FPM qualification models are built in advance of the flight models. The BEE EQM is currently undergoing mechanical and thermal qualification as well as performance testing. The SEM and FPM qualification models are being integrated at this stage and to be followed qualification as well. A very important milestone for the camera is the performance verification in thermal vacuum. The verification with the EQM gives an important insight into the performance of the instrument. These tests are scheduled in summer 2016 as well.

6. PERFORMANCE CONSIDERATIONS

The performance estimations of the instrument are mainly verified with a noise budget. Photometric performance is key to the mission and is closely monitored. In addition to the photometric noise, the observability map is considered as well which depends mainly on the orbit of the mission and the straylight rejection performances. This is however not detailed here.
The noise budget of the CHEOPS instrument depends on various parameters which origin from different noise sources. The contributions come from astronomical sources (e.g. shot or photon noise), noise sources from the instrument (e.g. CCD gain variability) and from the entire system (e.g. spacecraft jitter). This chapter gives a brief overview of the different noise sources considered and the current best estimate of the photometric performance based partly on measurements, partly on estimations. The results are given for three different star types respectively star magnitudes.
As already mentioned the performance of the instrument with respect to the photometric noise is influenced by many parameters. Hereafter the dominant parameters, which have been considered are listed with a brief description.

Noise contributor	Description
Shot noise	Shot noise is associated with the particle nature of the light. Since each photon is an independent event, the arrival of any given photon cannot be precisely predicted and thus creates a noise behavior which tends to a Gaussian distribution for a large amount of photons
Sky background	The sky background is a faint, diffuse white glow, which manifests as background light on the detector. This background manifests as shot noise as well.
Cosmic rays	Charge is generated on a pixel or several pixels of the CCD when being hit by a cosmic ray. These pixels can be corrected to a certain extent.
Earth stray light	Noise from Earth stray light is taken into account as the stray light suppression of the instrument is not perfect. This noise contributor is season and pointing dependent.
Jitter + Flat Field + Breathing	Jitter origins in the not perfect relative pointing accuracy and 'smears' the stellar PSF on the CCD. As the flat field correction is not arbitrarily good, this creates a noise contributor.
Read out noise (CCD)	The read out of the CCD creates a noise behavior which follows a Poisson distribution.
Dark current variation noise	There are two components to the noise associated with dark current. These are the shot noise associated with the dark current level, and the induced variation in the level of the dark current (largely as a result of temperature variation).
CCD Gain variability + QE change	The gain variability and QE change is taken into account as consequence of the temperature variation of the CCD.

Analog electronics stability	The analogue electronics stability is the noise contributor from the CCD bias voltage variability due to temperature variation, reference voltage variation, etc.
Offset in analog electronics stability	Offset errors are independent of the analog electronics stability and taken into account separately.
Timing error	Uncertainties in the knowledge of the exposure time lead to timing errors and thus noise contributions.
Quantization noise	The quantization noise is introduced due to the digitalization of the signal.
Analog chain random noise	This corresponds to the high frequency noise from the front end electronics on top of the read out noise.

Table 1: Photometric noise contributions and description.

Considering all the noise contributions listed in Table 1 an exhaustive noise budget has been established. As the project evolves, increasing amount of the contributors can be verified by test. Certain of the parameters can be directly measured and a few of them can only be estimated indirectly as for example the stray light rejection capabilities as this cannot be measured at system level.

Considering the current best estimate and knowledge of the noise sources, it can be stated that the science requirements related to the photometric precision mentioned in chapter 2 are met. Table 1 compares the photometric error with the requirement.

Case number	A	B	C
Stellar magnitude	6 (ST = G)	9 (ST = G)	12 (ST = K)
Error time average [ppm]	16.1	18.0	47.4
Requirement [ppm]	20	20	85

Table 2: Current best estimate of the noise budget for different brightnesses and spectral types (ST) of the target star.

7. CONCLUSIONS

The first small class mission (S-mission) in ESA's Science Program, CHEOPS, is currently in phase C/D. Half time through the development time of the mission, the instrument with its science objectives, instrument summary, major challenges, development status and performance estimations are described.

After successful PRR and SRR in 2013, PDR in July 2014, a complete instrument STM has been built and successfully tested at instrument and spacecraft level, including a challenging stability test with 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 in addition.

The instrument CDR has been passed successfully and the system CDR is expected to be closed mid-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.

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