CHEOPS launch in 2019! - Payload capabilities and in-orbit commissioning preview

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ABSTRACT

ESA Science Programme Committee (SPC) selected CHEOPS as the first small class science mission in 2012. CHEOPS is considered as a pilot case for the implementation of “small science missions” and its success is key for the continuation of fast-paced, small missions. The mission has been developed and brought into a flight readiness state within 5 - 6 years from selection, which is about half the time of other ESA missions. This paper focuses on the CHEOPS payload and its predicted capabilities. The 300mm effective aperture Ritchey-Chretien telescope provided by the CHEOPS consortium has been tested and characterized on ground in a 2 months calibration campaign after the qualification for flight. The results have led to performance estimations, which are discussed here. We show that the performance requirements in flight are expected to be met by the instrument. A preview is given towards the 2 months lasting In Orbit Commissioning (IOC) phase of the CHEOPS payload after LEOP and platform check-out. The activities in orbit range from dark current measurements, PSF characterization and parasitic stray light determination to AOCS and instrument performance verifications to science validation using reference transits.

INTRODUCTION

The first definitive detection of an exoplanet orbiting a Sun-like star has been made by Michel Mayor and Didier Queloz of the University of Geneva in 1995 [1]. Since then, a large number of exoplanets (4023 as per April 2019) were discovered using different techniques. The two most successful measurement techniques rely on radial velocity variations and photometric perturbation measurements. The radial velocity method measures Doppler changes in the emitting light of the parent star due to the presence of the planet using the binary mass function. The photometric perturbation or transit method measures the brightness drop of the parent star during a transit of the planet in front of it. The two methods complement each other such that the radial velocity measurement provides the mass while the transit measurement provides the radius of the planet. Using the combination of the two measurements gives a measure of the mean density.

Despite the two decades of high precision radial velocity measurements and highly successful space missions such as CoRoT and Kepler dedicated to transit searches, the fraction of exoplanets in the mass range 1-30 MEarth for which both mass and radius are known to a good precision is rather small. The fact that the high accuracy photometric space missions focused mostly on faint stars which is not beneficial for high accuracy Doppler measurements leaves essentially two populations of exoplanets, one for which we know the mass and one for which we know the radius with very little overlap. The CHOEPS mission is designed to bridge this gap and provide a large sample of high accuracy photometric data from bright stars.

CHEOPS MISSION

The CHEOPS mission has been selected by the ESA Science Programme Committee (SPC) in 2012 as part of ESA’s small class (S-Class) mission program. The mission was adopted in February 2014 as first S-Class mission. Being a small class mission, CHEOPS has been subjected to very tight schedule and budget constraints. The boundary conditions set by ESA have been a development time (phase B2/C/D) of maximum 4 years, a high level of technological readiness at proposal selection (TRL > 5), total cost to the ESA Science Program limited to 50 M€ and a total cost of less than 150 M€ (ESA + Mission Consortium). This corresponds to about 10% of the ESA budget for an M-Class mission and less than half of the development time. The cost-capped ESA budget has also implied a redistribution of responsibilities between the agency and its member states, the latter taking more responsibility than in other ESA missions.

CHEOPS is implemented in a partnership between ESA and Switzerland with several ESA Member States delivering significant contributions to the space segment and operations. The responsibilities are shared between ESA and the mission consortium, ESA in charge of providing the platform, the system level AIT and the launch opportunity while also acting as mission architect. The mission consortium is providing the payload, the science operation center and the mission operation center with ESA contributions in several areas.

The mission has been declared flight ready by passing the S-QAR review early 2019 and is awaiting the launch that is currently expected to happen between 15th of October and 14th of November. The remaining time until launch is used to finalize the spacecraft and payload and prepare for the Launch and Early Operation Phase (LEOP) and the In-Orbit Commissioning (IOC).

SCIENCE OBJECTIVES

A comprehensive summary of the science objective for the CHEOPS mission can be found in the ESA definition study report [2].

The main science goal of the CHEOPS mission will be to study the structure of exoplanets smaller than Saturn orbiting bright stars with revolution periods below 50 days. With an accurate measure of masses and radii for an unprecedented sample of planets, CHEOPS will set new constraints on the structure and hence on the formation and evolution of planets in the sub-Saturn mass range. In addition, CHEOPS will also follow a handful of hot giant planets [3].

A number of challenging science requirements are consequently posed to the instrument and the mission. The photometric accuracy requirements and the sky coverage are briefly recapped hereafter. The two topics are the main driver of the mission design.

Photometric accuracy

CHEOPS will target several different types of stars ranging from 6 to 12 magnitude. The photometric accuracy requirements depend on the brightness of the starts and are read as follows for the bright stars:

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 [3].

While for the faint stars, the precision requirement is reduced to:

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 [3].

The photometric performance requirements pose major challenges to the design of the instrument and the mission and will allow highly accurate radii measurements of the targeted exoplanets.

Sky coverage

As a follow up mission it is essential to be able to observe a large fraction of the sky. At mission conception a considerable amount of predicted targets for CHEOPS came from radial velocity surveys. Based on these characterizations the following requirement for the sky observability has been formulated:

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 [3].

In addition, CHEOPS targets were expected from ground-based transit surveys in the southern hemisphere. This led to the second requirement for sky coverage:

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.

CHEOPS MISSION DESIGN

The CHEOPS mission design was first consolidated at the end of 2012, based on a 3-month assessment study (phase 0/A) conducted at ESTEC, using the Concurrent Engineering Facility (CDF) [4]. After the CDF study, design iterations have been performed and the final mission design was concluded at the System Requirements Review (SRR). The following key design features have been used for the final design of the platform, payload and ground segment.

Orbit

A Sun-synchronous, dawn-dusk, orbit was chosen at the time of the SRR with an altitude between 650 and 800 km, later with a final altitude of 700 km.

Lifetime

The nominal mission lifetime has been set to 3.5 years with a possible mission extension to 5 years.

Spacecraft configuration

The spacecraft configuration has been chosen to ease the assembly of the payload and platform and guarantee as much as possible a parallel development. The payload is installed on top of the platform, behind a fixed Sun-shield supporting the solar arrays. The platform was required to have very compact dimensions to support different LV adaptors such as ASAP-S on Soyuz or VESPA on VEGA. Additionally the platform relies as much as possible on previous heritage.

AOCS design

The AOCS makes use of information from the instrument, namely the measured difference between the real PSF centroid position and the expected position. The information is fed to the AOCS in order to improve the pointing stability to below 4 arcsec over a 48h observing period. A rotation of the platform around the Line of Sight (LoS) was implemented in order to point the instrument radiators always away from the Earth.

The platform is capable of pointing the instrument line of sight within a half-cone of 60 deg centered around the anti-Sun pointing direction.

Debris mitigation

The platform hosts a compact, mono-propellant propulsion module to comply with the space debris mitigation regulations of re-entering Earth's atmosphere within 25 years after end of operations and to perform collision avoidance maneuvers.

Payload – Platform interface

The interfaces between the platform and the payload have been designed such that the respective entities can work in parallel as much as possible. The telescope and the baffle (detailed in the chapters below) of the payload have been accommodated using isostatic mounts for thermo-mechanical de-coupling. The star tracker optical heads are hosted by the payload in order to minimize the thermo-elastic deformation between them and the line of sight of the instrument.

The two electronics boxes of the payload are hosted inside the platform body where they are kept at operating temperatures. The software interfaces have been kept simple using a Mil-1553 bus. The commands and telemetry of the payload are transparent to the platform with the exception of the AOCS and heartbeat (FDIR purpose signal) interface.

CHEOPS PAYLOAD

The CHEOPS payload is a high performing photometer measuring light variations of mostly bright stars. The instrument is operating in the visible and near-infrared range (0.4 to 1.1µm) using a back illuminated CCD detector run in AIMO mode. The telescope is making use of a Ritchey-Chretien optical configuration with a 320mm diameter primary mirror. Considering the central obscuration of the primary mirror, the effective collecting area of the system is 76793 mm2.

The instrument is composed of four different units, which are mounted on the top deck of the platform in case of the telescope and baffle and inside the platform body in case of the two electronics boxes. The units are the following.

Optical Telescope Assembly (OTA)

The OTA hosts the optics as well as the detector and the read-out electronics of the instrument. The optical configuration consists of a Ritchey-Chretien telescope and a Back End Optics (BEO) to re-image the telescope focal plane on the detector and to provide an intermediate pupil where a pupil mask is placed for stray-light rejection. The telescope focal length is 1600mm, giving a telescope focal ratio of F/5. The 0.32 degrees field of view is translating into a 1 arcsec/px plate scale on the detector (13-µm pixel 1k × 1k, AIMO). Figure 1 illustrates the OTA/BCA assembly CAM/CAD cut view. The TEL group with the primary and secondary mirror, the BEO and the focal plane module (FPM) are indicated.

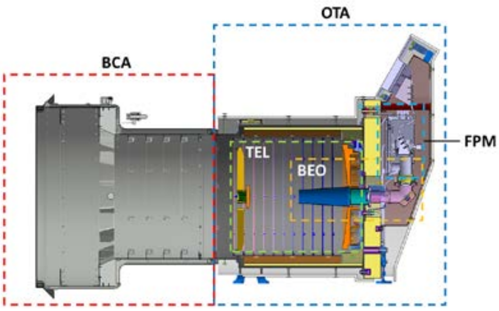

Figure 1: OTA/BCA assembly.

The focal plane module hosts the CCD and the read out analogue and digital electronics. The CCD is nominally operated at 233K and temperature stabilized within 10mK while the read-out electronics are stabilized to 50mK. The excess heat from the FPM is being radiated to deep space using two passive radiators on top of the OTA. The need of temperature stabilization comes from the need of having very stable and low noise CCD read out. Low operating temperatures minimize the read out and dark noise in the system while temperature stability minimize dark noise variation and especially the CCD gain variability, QE change as well as the analogue electronics stability.

CHEOPS uses a defocused point spread function (PSF) to enhance the performance. This is a trade-off between the pointing jitter introduced by the AOCS performance and the flat field performances. The PSF has therefore been chosen to be 12.5px in radius at operating temperature in orbit. The main drawback of the trade-off is the introduction of aberrations in the optical system, which complicated the optical alignment.

Baffle and Cover Assembly (BCA)

The BCA is key to the stray light mitigation strategy of the payload. The baffle design has been adapted from the CoRoT baffle but scaled down in size. This strategy has been well suited for the S-class mission. The baffle consists of a cylindrical, aluminum part, containing circular vanes and black coating for stray-light rejection, and a cover assembly part. The cover assembly is a one-shot cover that protects the payload cavity, the optics, from contamination issues during AIT as well as during launch and early operations phase. The cover release mechanism is based on a spring-loaded hinge and a launch lock mechanism. The launch lock makes use of a Frangibolt actuator design.

Figure 2 shows an image of the structural and thermal model (STM) of the instrument. The view shows the instrument cavity from the front. The cover MLI has been removed for these tests (final configuration in Figure 3). On the left side of the BCA the hinge can be seen. The Frangibolt is enclosed on the right hand side.

Figure 2: Picture of the STM instrument.

The BCA and OTA are mechanically mounted on separate parts of the platform. The BCA to OTA interface is sealed by a Vetronite seal in order to close off the complete cavity.

The baffling system of the instrument, including the OTA baffling is designed to be able to reject a significant amount of stray light from angles greater then 35° from the optical axis. The level of stray light suppression required by the baffling system is in the range of 10^{-10} to 10^{-12} depending on the incidence angle.

Sensor Electronics Module (SEM)

The SEM is located inside the platform and controls the FPM. The SEM is hosting the Sensor Control Unit (SCU) and a Power Conditioning Unit (PCU). The FPM and SEM have been adapted by DLR Berlin from their MERTIS camera flown on ESA's BepiColombo mission. The SEM itself interfaces the Back End Electronics (BEE) on the other side and is commanded through it. The functions and characteristics of the SEM can be summarized as follows [5]:

- Digital control electronics (FPGA including a LEON processing unit, RAM, EEPROM, PROM) for clocking the CCD/FEE, reading out the CCD and processing of data.
- Generate clocking modes for different CCD read-out modes.
- Perform thermal control of the CCD and FEE
- Voltage conditioning towards the FPM
- Windowing of CCD image getting a 200x200 star window and overscan windows

- Time stamping of CCD and HK data.
- Sending reference star images to the BEE for AOCS processing/interface test.
- Analog Housekeeping acquisition by a separate ADC.

In summary, the SEM/FPM represents the camera of the CHEOPS instrument that is controlled by the BEE as a higher-level computer.

Back End Electronics (BEE)

The BEE is the main computer of the instrument. On the one hand, it provides power and data interface to the On Board Computer (OBC) of the platform, on the other hand, it interfaces the SEM. Similarly as the SEM, it provides a Data Processing Unit (DPU) and a Power Supply and Distribution Unit (PSDU). 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 mass memory from 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 32-bit access and EDAC.
The BEE is hosting the main instrument software, the IFSW, which provides a high-level control of the SEM and FPM. Additionally its main functions are to perform the data handling, the centroiding of the stellar image that is used by the AOCS and the data compression.

PAYLOAD PERFORMANCE

The performance of CHEOPS is defined by several noise sources contributing to the total noise behavior. As seen above, the performance requirements in terms of noise are given for two different stellar magnitudes of the targets, a bright one ($6 \leq V \leq 9$ mag) and a faint one ($9 \leq V \leq 12$ mag). Extensive noise calculations have been performed on the basis of measurements obtained during the flight model acceptance tests and calibration campaign in 2018. This allowed to validate the requirements for the science performance and predict the behavior in flight. Hereafter the various noise sources that have been considered are briefly explained. Generally two different sources are considered originating either from the environment or from the instrument/satellite itself. The extrinsic, astrophysical noise sources are the:

- Photon noise,
- Zodiacal light,
- Cosmic ray effects,
- Stray light contributions.

Whereas the instrument/satellite noise consists of:

- PSF + Jitter + Flat Field (+ Breathing) noise,
- Read-out noise
- Dark current variation
- CCD gain variability
- Analog electronic stability
- QE variation
- Timing error
- Quantization noise
- Bad pixels.

In this paper, we are not discussing all the different noise contributors but have a closer look at the sources, which posed the major challenges to the mission. We briefly touch three noise contributors that are the CCD gain variability, the Jitter and the Earth stray light.
The three sources are chosen because they dominate the performance and are mainly taken into account in the instrument design.

CCD gain variability

For a high precision photometer, the CCD gain needs to behave as stable as possible. With the CHEOPS CCD, as part of the flight selection process, gain sensitivity measurements were performed at the University of Geneva. Figure 3 shows the CCD mounted inside the cryostat used for the flight unit characterization.

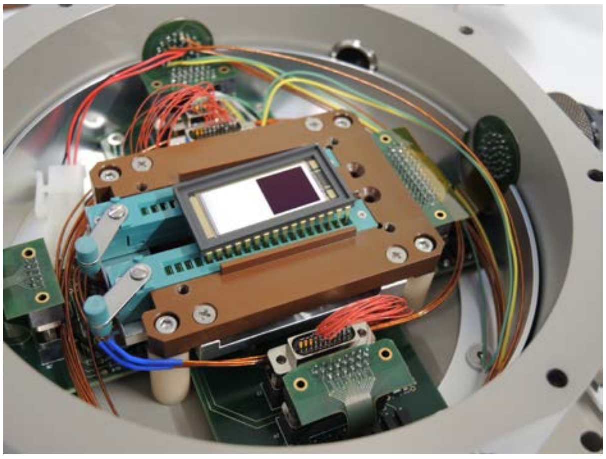

Figure 3: CHEOPS CCD mounted in the cryostat of the University of Geneva.

The CCD gain (the ratio between the number of electrons per pixel and number of counts per pixel) sensitivity depends on temperature and operating voltage. Both dependencies were characterized. In the case of temperature, it is in the order of 1ppm/mK of noise. The operating voltages dependency is slightly more complex and depends on which voltage is being looked at. Generally, the dependency of these contributors are between 5 and 40 ppm/mV. This fact lead to the need of maintaining very stable temperatures and voltages for the CCD. Especially the voltages were a major challenge to the instrument. Predictions, on the CCD gain sensitivity contributions to the overall noise budget (together with the QE stability) based on calibration measurements show that the contributor is in the order of 3 – 10 ppm.

Jitter

The Jitter or AOCS pointing instability does affect the position of the point spread function (PSF) on the CCD and has different causes. On one side, the AOCS system does inherently contribute a certain pointing error with the use of star tracker and reaction wheels, on the other side a thermoelastic bias can contribute to the error. Thermoelastic deformation between the AOCS reference system and the payload reference system (or line of sight) impacts on the PSF position. In order to avoid as much as possible these effect, two countermeasures have been implemented into the design. First, the star tracker optical heads have been integrated onto the payload itself in order to minimize the thermoelastic effect. Figure 4 shows an image of the payload flight unit after integration on the platform. One star tracker optical head is visible on the side of the instrument (with the red remove before flight cover).

Figure 4: Picture of the payload after integration on the platform with the star tracker optical heads (red covers). Image credits Airbus DS Spain.

In order to compensate the pointing errors, a payload in the loop system has been introduced. The platform AOCS makes use of the centroid information from the payload in order to compensate the thermoelastic deformations. To be able to perform this, the instrument calculates for each acquired image the centroid of the target star PSF. The distance of the centroid to the desired location of the star on the CCD is sent to the platform AOCS, which corrects for it. In this way, the required AOCS performance of 4-arcsec stability (at 68% confidence level) is achieved. The correction is used as well in the case of the first acquisition of the star as the absolute pointing accuracy is lower than the relative one. The target star is in this case moved to the desired location on the CCD in order to start the measurement.

The pointing accuracy contributes to the total noise of the system mainly because of the pixel-to-pixel knowledge of the flat field variation. The variation cannot be measured to an arbitrary precision but to about 0.1% accuracy. In order to compensate the error introduced by moving the PSF over different pixels (because of the jitter), the PSF has been chosen to be defocused. By illuminating a larger amount of pixels with one star, the introduced error is significantly reduced.

Straylight

The third major contribution to the overall noise budget is the straylight introduced by the Earth. The values of the stray light contamination are pointing and season-dependent. Avoiding effects of straylight contamination is done in two different ways. The payload has been designed with a dedicated baffling system in order to limit the amount of straylight for sources more than 35deg from the optical axis. The suppression capability of the baffling system has been estimated based on indirect measurements of the hardware (e.g. coating BRDF, vane edges, etc.). The capability is dependent on the angle of incidence but the suppression reached a factor of 10^{-12} at high angles above 60deg. The point source transmission function (PST) does as well show a significant dependency with particulate contamination of the mirrors and lenses. The requirement set for the contamination on the mirrors has been 200ppm upon delivery of the payload to the platform provider. This has been a major impact in the payload AIV process requiring to perform all of the operations in ISO5 cleanrooms. On the on-ground post processing side, a straylight removal of the images is implemented in addition. According to the heritage of CoRoT and to our own semi-analytical estimations, the stray light is further reduced by 99.6%. The noise contribution to the overall budget is distinguished between 5ppm noise for a star of magnitude 9 and 70ppm for a star of magnitude 12.

PERFORMANCE ESTIMATIONS

As anticipated in the previous chapter, different contributors of noise have been identified and taken into account in the CHEOPS design. A few of them have been discussed in more detail. This chapter makes a summary of the noise budget and compares to current estimates to the scientific requirements posed at the mission. The overall noise figures are composed of a white noise parts where the noises average with time and systematic noises that do not. Generally, the white noise terms are the shot, read out, dark, cosmic ray, etc., noises and the systematic noise terms are from straylight, flat field, jiiter, etc., noise contributors. In the noise budget we give three cases with different star magnitudes (6, 9 and 12) as reference cases. The time-averaged error with integration times of 6h, 6h and 3h, respectively, are shown for the nominal case and the best estimate [6].

Table 1: Noise budget summary.

Case	A	B	C
Mv star	6 (ST = G8)	9 (ST = G8)	12 (ST = K5)
Exposure Time [s]	1	10	60
Integration time [h]	6	6	3
Error (nominal) [ppm]	17.5	19.3	86.1
Error (best estimate) [ppm]	9.8	12.6	83.6

The comparison to the requirements shows that for bright starts the values can be achieved more easily than for fainter ones. However, it is shown that the science requirements are met for the mission. The dominant noise sources contributing to the overall noise depend on the stellar magnitude. Figure 5 and Figure 6 illustrate the noise behavior for the different stellar magnitudes of 6≤V≤9 mag and 9≤V≤12 mag respectively [7]. It can be seen that for bright stars, the noise contribution from the instrument dominates with minor photon noise effects. However, when observing faint stars, the straylight and the photon noise start to dominate.

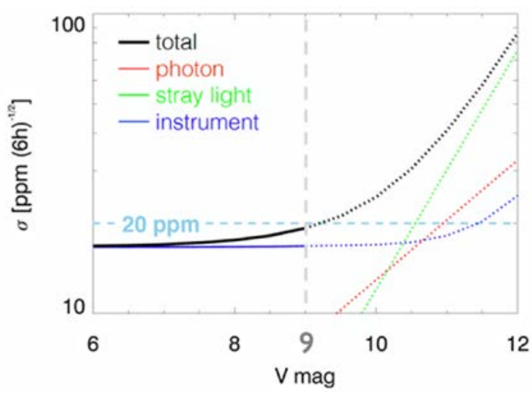

Figure 5: Noise budget bright stars.

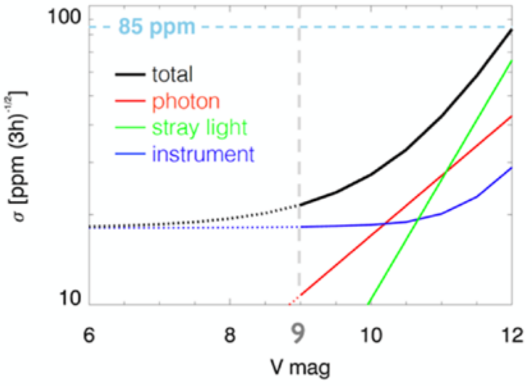

Figure 6: Noise budget faint stars.

From the qualification and calibration measurements performed at instrument and at satellite level it can be seen that certain noise contributors are more reliably measureable than others are. Naturally, those are more difficult to estimate in orbit. The commissioning phase of the CHEOPS mission will provide a comprehensive view on all aspects of the error/noise sources and satellite behavior but certain aspects are more eagerly anticipated.

IN ORBIT COMMISSIONING

The CHEOPS commissioning phase starts immediately after the launch and early operations phase (LEOP) that will last for one week. The commissioning phase is expected to last two months and will verify all performance aspects of the mission. The phase will end with the IOCR review. The LEOP and IOC operations are centralized at the National Institute of Aerospace Technology (INTA) in Torrejon de Ardoz close to Madrid. INTA hosts the mission operations center (MOC) for the CHEOPS mission. The responsibility for LEOP and IOC has been delegated to Airbus DS Spain by ESA.

The commissioning is divided into four different phases from IOC-A to IOC-D where different requirements are validated. The different phases differ in objectives, involvement of the different stakeholders and in complexity. Starting from instrument functional checkouts in the early phase A and CCD calibration measurements when the aperture cover is still closed to the cover opening and first light end of phase A. Figure 7 gives an idea of how the first light of CHEOPS can look like. It shows a simulated image of the payload where the PSF has been introduced as measured on ground. It shows a view to 55 Cancri, which is located at the very center of the image. The target shown here is a relatively bright star of magnitude 6 imaged using an exposure time of 0.5s.

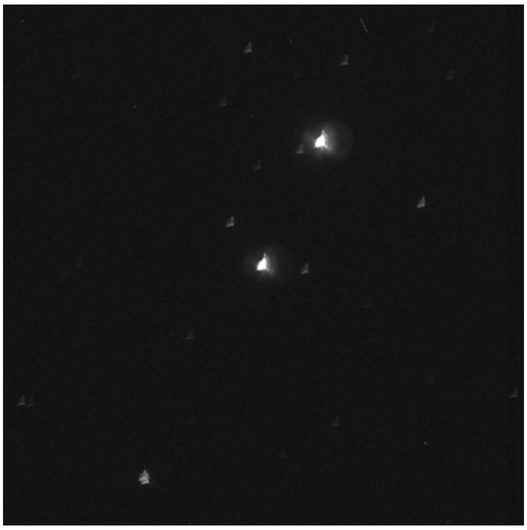

Figure 7: Simulated full frame image of 55 Cancri (center of the image).

The subsequent phase B will focus on optical verifications of the instrument including distortion, plate scale and PSF measurements; verify pointing stability with and without payload in the loop under different conditions including occultation and different field crowding. In addition, the straylight contribution to the noise budget is measured for different pointing configurations. All the read-out modes of the payload are tested and the SAA model, which is applied for CHEOPS, is validated. In the end of phase B all monitoring and characterization activities that are intended to be performed in a moderate frequency over the mission lifetime are exercised as a reference. Those include PSF, dark current, stray-light, flat field, gain and FWC monitoring as well as a so-called pinning curve measurement. The pinning curve is a measure for radiation damage on the CCD detector. The phase B is therefore very densely packed and gives a comprehensive view on the mission performance. Phase C verifies end-to-end science performance using, among other measurements, reference transits including the full data processing chain.

Phase D demonstrates the nominal mission capabilities including the one-week mission planning and MTL uplink. The phase can also contain low priority activities that are needed to be re-run from the previous phases. In general, phase D verifies the capability of the full space and ground segment to go into the nominal mission phase. At the end of the phase, the IOC is concluded with the IOC review, which marks the point of the handover of the satellite to the mission consortium.

CONCLUSIONS

The first ESA small class mission has been developed, built and tested in a close collaboration of ESA and the mission consortium. The mission has been cleared for flight early 2019 by ESA and is awaiting its launch on a shared Soyuz ST-A/Fregat operated by Arianespace in an October-November time slot.

The CHEOPS mission framework including details on the scientific payload was outlined here. The science objectives have been explained and the mission performance estimations were discussed. From the noise considerations, we saw that the mission complies with the science requirements. Overall, the performance estimations show very encouraging results.

We have shown the plans for the in orbit commissioning where the full system including space and ground segment are validated. LEOP and IOC will mark the end of the development and validation phase and the transition to the nominal science operation. We are all looking forward to the time when the CHEOPS mission finally is able to contribute to the scientific community with its valuable observations.

Acknowledgments

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