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CHEOPS – first ESA small scientific mission Ready to launch

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Abstract

The European Space Agency (ESA) Science Programme Committee (SPC) selected CHEOPS (Characterizing Exo-planets Satellite) in October 2012 as the first S-class mission (S1) within the Agency's Scientific Programme, targeting launch readiness by the end of 2018. The CHEOPS mission is devoted to the first-step characterization of known exoplanets orbiting bright stars, to be achieved through the precise measurement of exo-planet radii using the technique of transit photometry. It is implemented as a partnership between ESA and a consortium of Member States led by Switzerland.
CHEOPS is considered as a pilot case for implementing "small science missions" in ESA with the following requirements: science driven missions selected through an open Call for missions (bottom-up process); spacecraft development schedule much shorter than for M (medium) and L (large) missions, in the range of 4 years; and cost-capped missions to ESA with possibly higher Member States involvement than for M or L missions.
To reach its scientific goal of accurately characterizing exoplanet sizes, CHEOPS instrument will measure photometric signals with a precision of 20 ppm in 6 hours of integration time for a 9th magnitude star and a precision of 85 ppm in 3 hours integration time for Neptune-size planets orbiting 12th magnitude star. By being able to point at large portion of the sky, with 50% of the whole sky accessible for 50 cumulative days of observations per year, CHEOPS will provide the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based Doppler surveys.
The instrument provided by a consortium led by the University of Bern is an optical Ritchey-Chretien telescope with 300 mm effective aperture diameter, which provides a defocussed image of the target star on a single frame-transfer backside illuminated CCD detector. Straylight is minimized using a large external baffle and a dedicated field stop.
AIRBUS DS Spain was awarded with the contract to manufacture and integrate the satellite platform, the integration of the scientific instrument, the realization of the satellite functional and environmental campaigns, the launch campaign and the LEOP (lunch and early operation phase) and IOC (in orbit commissioning) phases. The platform is based on heritage from AS250, which is a compact, high performance and flight proven design.
The paper reports the Cheops satellite readiness for flight, including instrument calibration and spacecraft environmental test campaign and the preparation for launch which is planned for November 2019 on a shared Soyuz launcher.

1. Introduction

In October 2012 the CHEOPS (CHaracterizing ExOPlanet Satellite) mission was selected by the Science Program Committee (SPC) of the European Agency (ESA) to undergo an assessment and definition phase study as S1 (first S-class mission). Small class missions are much smaller in scale than the large (L) and medium (M) class missions of the ESA Cosmic Vision programme, with a drastically shorter implementation time and a strictly cost-capped budget. In February 2014, at the completion of the phase A/B1 activities, the Science Programme Committee (SPC) adopted

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CHEOPS for implementation as an ESA mission, in partnership with Switzerland and with important contributions from Austria, Belgium, France, Germany, Hungary, Italy, Portugal, Spain, Sweden, and UK, cooperating within a dedicated Mission Consortium.

CHEOPS is a follow-up mission, dedicated to searching for exo-planetary transits by performing ultra-high precision photometry on bright stars already known to host planets [1]. It will provide the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based spectroscopic surveys, providing on-the-fly characterization for exoplanets located almost anywhere in the sky. It will also provide precise radii for new planets (Neptune-size) discovered by the next generation of ground- or space-based transits surveys. By unveiling transiting exoplanets with high potential for in-depth characterization, CHEOPS will also provide prime targets for future instruments suited to the spectroscopic characterization of exo-planetary atmospheres.

In May 2016, CHEOPS passed the system CDR, less than two years after the spacecraft development kick-off, and following the integration of the platform with the instrument in mid 2018 and the spacecraft environmental test the satellite is now ready for launch aboard Soyuz expected for November 2019.

2. Small class boundaries and CHEOPS requirements

2.1 Small-class missions

In March 2012 the Science Directorate of the European Space Agency released the Call for the first small-class science mission (S1). The Call did not constrain the specific contributions of ESA and its member states as long as there was a clear leadership in the mission’s development and was open to all science themes, with the intention to explore the broadest possible range of small mission opportunities within the European scientific community. The boundary conditions set by ESA in the Call are summarized below [2]:

- a development time (phase B2/C/D) not exceeding 4 years;
- a high level of technology readiness at proposal selection (TRL > 5);
- a total cost to the ESA Science Programme limited to 50 M€ (at 2012 economic conditions);
- total cost less than 150 M€ (approximately, ESA + Member States).

The fast development time represents a key feature of the small-class missions and it is meant to provide the scientific community with faster access to space (~ 5-6 year from initial mission proposal to launch) compared to medium- or large-class missions (typically exceeding 12 years). In order to meet such a demanding schedule, the mission must rely on a high level of technology readiness for both platform and instrument. The limited cost envelope is constraining the mission scope and objectives and, in combination with the fast track development, calls for the adoption of existing and already flight-qualified small platforms within a defined set of orbits and mission profiles. The cost-capped ESA budget has also implied a redistribution of responsibilities between the agency and its member states, the latter taking responsibility for the provision of the ground segment as well as of the instrument.

The selection of the proposals received in June 2012 was based on a two-step approach: a first technical and programmatic screening (aimed at verifying the compatibility of the proposals with the boundary conditions set in the call [2]), followed by scientific screening and evaluation of proposals found to be within the programmatic scope of the Small Missions Call. In October 2012, CHEOPS was recommended for selection as S1 by the ESA science advisory structure and formally selected by the Science Programme Committee shortly after.

2.2 The CHEOPS proposal & share of responsibilities

The CHEOPS proposal was based on a cooperative scheme, with ESA, Switzerland and a number of other member states (Austria, Belgium, France, Germany, Hungary, Italy, Portugal, Sweden and UK, joined in 2014 by Spain) providing different contributions to the mission and working together within a dedicated Mission Consortium. In order to meet the boundary conditions set in the call and at the same time guarantee clear mission leadership and interfaces, the responsibilities summarized in table 1 were defined. These responsibilities are in line with an ESA-led mission, implemented in partnership with Switzerland and with important contributions from several other members states. It should be noted that the provision of the scientific payload from the Member States is customary for ESA science missions. In the case of CHEOPS the Mission Consortium, composed of several Members States, contributes also to operations.

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Table 1 – CHEOPS Mission Consortium and share of responsibilities.

Role	Responsible party	Remarks
Mission Architect	ESA	Overall mission definition
Platform procurement	ESA	Procured via spacecraft contractor (including specific operational SW tools)
Spacecraft (S/C) AIT	ESA	Via spacecraft contractor, supported by TAS CH as AIT service provider
Launch procurement	ESA	Shared launch opportunity
LEOP and IOC	ESA	Executed by the spacecraft contractor
Instrument	Mission Consortium	Led by the Mission Consortium in charge of calibrated instrument delivery; CCD, structure, BCA, BEE, radiators procured by ESA/Prodex
Science Team	Mission Consortium	Chaired by ESA
Mission Operations	Mission Consortium	Mission Operations Centre with ESA contributions
Science Operations	Mission Consortium	Science Operations Centre in charge of mission planning and monitoring and evaluating science performance

2.3 The mission requirements

The CHEOPS mission level requirements are derived from the combination of the science requirements (derived in turn from the science objectives of the mission) and the small-class boundary conditions. Details of the CHEOPS science objectives can be found in [1] and [3]. The science requirements can be found in full in [10] and in summary in [4] and are shortly reminded below:

- Photometric precision: in order to be able to detect Earth-size planets transiting bright stars, CHEOPS shall reach a photometric precision of 20 ppm (signal to noise ratio, SNR=5) on an Earth-size planet transiting a G5 type star (stellar radius of 0.9 R_{Sun}) with a V-band magnitude of $6 \leq V \leq 9$ in 6 hours of integration time. The integration time corresponds to the duration of the transit of such a planet with an orbital period around its host star of 50 days. To be able to characterise transits of Neptune-size planets, CHEOPS shall reach a photometric precision of 85 ppm (SNR=30) on a Neptune-size planet transiting a K-type (stellar radius of 0.7 R_{Sun}) with a V-band magnitude of $V \leq 12$ in 3 hours integration time. In this case, the integration time corresponds to the duration of the transit in such a planet with an orbital period of 13 days.

  Given the differential nature of a transit measurement, it is essential to establish a precision measurement of the out-of-transit light curve. This, together with the need to allow for drifts in the transit ephemeris, errors in the ephemeris due to uncertainties in the orbital eccentricity and the need to observe phase curves of hot, short-period giant planets, sets a timescale for maintaining these precision requirements of 48 hrs.

- Sky coverage: as a follow-up mission, CHEOPS targets will be distributed over the whole sky. To maximise the chances of catching a planetary system in transit, the detection biases associated with the different classes of CHEOPS targets have been used to set requirements on the fraction of sky for which the photometric precision requirements above shall be met or exceeded, considering constraints imposed by Sun, Moon, and Earth stray-light, as well by interruptions in the observations caused by occultation of the target by the Earth and by passage of the spacecraft through the South Atlantic Anomaly. For the small mass planets discovered by radial velocity surveys, 50% of the whole sky shall be accessible for 50 cumulative days per year and per target, with the time spent on-target and integrating the target flux to be longer than 50% of the spacecraft orbit duration. For Neptune-like exoplanets detected by the NGTS facility located at ESO's Paranal Observatory in Chile, which in turn covers ~10% of the southern sky, 25% of the whole sky, with 2/3 in the southern hemisphere, shall be accessible for 13 cumulative days per year and per target, with the time spent on-target and integrating the target flux to be longer than 80% of the spacecraft orbit duration.

- Mission lifetime: a nominal mission lifetime of 3.5 years is required to complete a programme that encompasses the science objectives of the mission, with a goal of an extended mission duration of 5 years. 80% of the observing time is assigned to the CHEOPS Mission Consortium (Guaranteed Time Programme), with the remaining 20% constituting the Guest Observers Programme that will be run by ESA through open, competitive Announcements of Opportunity to the Scientific Community.

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3. Development challenges

3.1 Main challenges

The key development challenges of CHEOPS are dictated by the demanding schedule and budget constraints, combined with the objective of scientific excellence. In fact the cost of CHEOPS for ESA (capped at 50M€ and including, among other contributions, the procurement of the platform and the launch) represents approximately 10% of the ESA budget for the M-class missions; similarly, the maximum CHEOPS development time of 4 years is less than half of the typical development time for the M-class missions. The main challenges can be summarized as it follows.

- A multi-party cooperation: the CHEOPS mission is based on a multi-party cooperative scheme. Although ESA is the mission architect, the Mission Consortium is providing not only the instrument (as is customary in the ESA science missions), but is also leading the Ground Segment development and operations. Several institutes, under the leadership of the University of Bern, are interacting so as to meet strict deadlines, requiring timely and close coordination. The instrument consortium includes more than 15 research centres and industries from 6 different countries, the S/C contractor leads a consortium of 18 companies from 10 different countries, and the ground segment also involves some 10 organizations from 7 member states.

- A newly designed instrument: the CHEOPS payload is designed specifically for this mission. Although the instrument did not require technology development, its design has demanding performance requirements (e.g. photometric precision of better than 20 ppm over integration periods of 6 hours) and the completion of a full development, qualification and calibration programme in less than 5 years represents a significant challenge.

- Definition of P/L to P/F interfaces: given the very tight planning, the definition of the instrument-to-platform interfaces must progress in parallel to the corresponding design phases, imposing a concurrent engineering approach and very frequent interactions between the involved technical teams.

- Flight qualified solutions: as a consequence of the fast development approach and limited budget, the project needed to rely on existing flight heritage and solutions, thus constraining the number of possible design options.

- Shared launch opportunity: the available budget has imposed from the start the need to design the satellite to be compatible with shared flight opportunities, with two main implications: a) size and mass limitations imposed by existing launcher performance and dispensers; b) a more complex launch opportunity procurement.

- Multi-Launcher compatibility: given that the operational orbit required to meet the scientific requirements (a dawn-dusk Sun-Synchronous Orbit) is not frequently used, it was important to retain compatibility with different launch vehicles, so as to maximize the number of potential flight opportunities. On this basis, the satellite design has been required to be compatible with different medium and small-size launchers.

- Development practices & quality standards: although characterized by a small budget and a fast-track development, CHEOPS needed to remain compatible with the development practices and quality standards applicable to all ESA missions.

3.2 Project implementation approach

In order to meet the CHEOPS mission development challenges, a number of measures were adopted in setting up the project organization and defining the implementation approach [2]. These are summarized below.

1) Project organization: small size teams were deployed to maintain close coordination as well to enable a faster decision process (e.g. the ESA CHEOPS team is composed of only five full-time members).

2) Technology readiness: the Call for the S1 mission requested the mission concept to be compatible with the re-use of an existing “off-the-shelf” platform and to include a payload based on available technologies (TRL > 5-6 in ISO scale), ruling out complex development activities and focusing on implementation and flight qualification aspects.

3) Stability of requirements: both the accelerated development schedule and the mission cost ceiling required very stable requirements from the start of the project. Significant work was performed to consolidate the requirements by the System Requirements Review (SRR) and, later in the project, to avoid modifying or adding requirements. The CHEOPS requirements have remained remarkably stable and minor modifications were only allowed after the project reviews and implemented in agreement with the spacecraft contractor and the instrument team.

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4) Industrial implementation approach: as described in [6] and in contrast to the M- and L-class missions, a single Invitation to Tender was issued for CHEOPS, covering both a parallel competitive study phase (A/B1) and the implementation phase (B2/C/D/E1, including responsibility for Launch and Early Operation Phase - LEOP and In-Orbit Commissioning - IOC). Compatibility with a ceiling price for the implementation phase was requested to the bidders, to be converted into a firm fixed price after the SRR, when final requirements were agreed and the prime contractor was selected. Given the very tight schedule and the platform heritage, the spacecraft prime contractors were allowed to select the equipment suppliers through direct negotiation, before submitting their final bid.

5) Early mission concept definition: the industrial procurement approach described above (single tender with a ceiling price covering also the implementation phase) is only feasible when the mission concept and the space segment requirements and early design are mature enough to rule out major changes in later phases. This is especially challenging considering the inherent uncertainties of a science mission and the development of a new instrument, and considering that the tender for the industrial procurement of the platform and spacecraft integration was released only 5 months after the start of the ESA internal assessment activities. A concurrent engineering approach (in the form of a phase 0/A study performed at the Concurrent Design Facility at ESTEC) was applied in order to achieve the required mission concept maturity in such a short time.

6) Definition of interfaces: the early definition of clear and stable interfaces (instrument-platform, spacecraft-ground, spacecraft-launcher) was requested to all parties as an essential pre-condition to ensure that the different teams could work in parallel and meet their challenging development schedules. Frequent interface technical meetings have been organized with ESA, as mission architect, playing an important coordination role.

7) Review cycle: the CHEOPS project has followed the standard ESA review cycle. However, in order to maintain compatibility with the stringent schedule constraints, the duration of the reviews was compressed compared to other larger missions, adapting the number of panels and reviewers to streamline the process.

Overall, this implementation approach has allowed to select the prime contractor and start the implementation phase (B2/C/D/E1) in April 2014, only 1.5 year after the initial mission proposal selection (October 2012), and to complete the system Critical Design Review (CDR) in May 2016 (3.5 years from proposal selection) and the qualification review in 2018. Figure 1 summarizes the main past milestones in the development of CHEOPS.

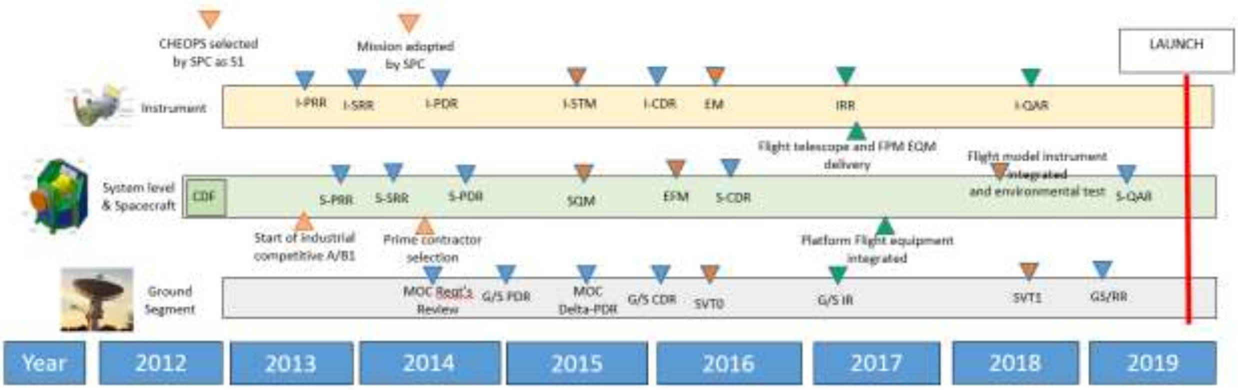

Figure 1 Main Cheops milestones

submitting your paper. The papers will be typeset on A4 paper with top, lateral and bottom margins of 30, 22 and 25 millimetres, respectively. A single column format is to be used. The paper should be typeset in either Times or Times New Roman font, 10 point size. The section and subsection titles should be typeset according to the format and weight of the present template.

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Mission Spacecraft and Design

4.1 Mission summary

The CHEOPS mission design was first consolidated at the end of 2012, on the basis of a 3-month assessment study (phase 0/A) conducted at ESTEC, using the Concurrent Engineering Facility (CDF). The main objectives of the assessment study were: a) confirmation of compatibility of the mission concept with the existing boundary conditions; b) definition of the mission and system level requirements; c) analysis of alternative design solutions via dedicated technical trade-offs; d) consolidation of the satellite configuration and associated resource budgets; e) preliminary definition of the instrument to platform interfaces. The assessment study played a critical role in the preparation of the invitation to tender to industry for the parallel competitive definition study (phase A/B1). The mission design resulting from the phase 0/A study was remarkably close to the final design iterations performed as part of phase A/B1 and presented first at the Preliminary Requirements Review (PRR) and then at SRR. By the time of the SRR, the mission profile and overall S/C design were consolidated, with the following key design features:

- the selection of a dawn-dusk, Sun-synchronous orbit, with an altitude to be chosen between 650 and 800 km and a nominal operational phase of 3.5 years (with a recently indicated preference for an altitude of 700 km)

- an AOCS design using information from the instrument to maintain the commanded pointing direction (payload-in-the-loop), thus removing residual thermal-distortion effects and improving pointing stability to better than 4 arcsec. A spacecraft rotation around the telescope Line of Sight (LoS) is also implemented, so as to maintain the instrument radiators pointed to cold space

- a spacecraft configuration driven by the installation of the instrument on top of the platform, behind a fixed Sun-shield, also supporting the Solar Arrays, and with compact dimensions, so as to fit within different LV adapters (e.g. under ASAP-S on Soyuz and under VESPA on VEGA)

- the capability to point the instrument line of sight within an half-cone of 60 deg centred around the anti-Sun direction

- the inclusion of a compact, mono-propellant propulsion module, required in particular to comply with the space debris mitigation regulations of re-entering Earth's atmosphere within 25 years from the end of operations

- instrument-to-platform interfaces based on iso-static mounting of the instrument Baffle Cover Assembly (BCA) and of the Optical Telescope Assembly (OTA) on the top panel of the platform; thermal de-coupling of the instrument from the rest of the S/C (with the exception of two instrument electronic units installed inside the platform), and installation of the optical heads of two star-trackers directly on the OTA (to minimize misalignment induced by thermo-elastic distortion).

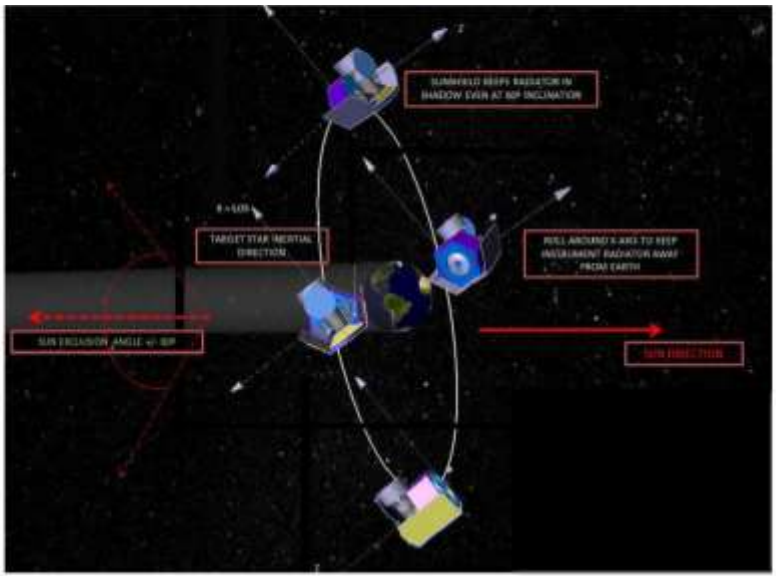

Figure 2: CHEOPS spacecraft attitude and pointing directions in the operational orbit

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4.2 The CHEOPS Instrument

The CHEOPS instrument is a high precision photometer operating in the VIS and NIR range (0.4 to 1.1 um) [5]. It has a total mass of approximately 60 kg and a power budget of about 55 W. and is being developed by an instrument consortium led by the University of Bern (CH). The instrument is composed of 4 main units:

- the Baffle Cover Assembly (BCA), providing protection from stray-light and including a single-operation cover used to minimize contamination during the flight satellite test activities and launch.

- The Optical Telescope Assembly (OTA), including an on-axis, Ritchey-Chretien telescope with a clear opening diameter of 32 cm and designed to operate between 0.4 and 1.1 um. The optical design includes a Back-End Optics, relaying light to the Focal Plane Module (FPM). The FPM hosts a single back-illuminated CCD (e2V, CCD47-20, 13 um pixels, 1k x 1k), operating at -40 deg C in AIMO (Advanced Inverted Mode Operation), with a temperature stability better than 10 mK. The Front End Electronics is operated at –20 deg C. These operating temperatures are achieved by means of two dedicated radiators, both protected by the S/C Sun-shield.

- The Sensor Electronic Module (SEM), with the function of controlling the FPM and accommodated as a separate unit inside the platform.

- The Back-End Electronics (BEE), providing overall instrument control and including Data Processing Unit and Power Supply and Distribution Unit. The BEE is also accommodated inside the platform.

Figure 3 shows the overall instrument configuration, with BCA and OTA, which are accommodated on the top panel of the platform. BEE and SEM are installed inside the platform (see figure 4).

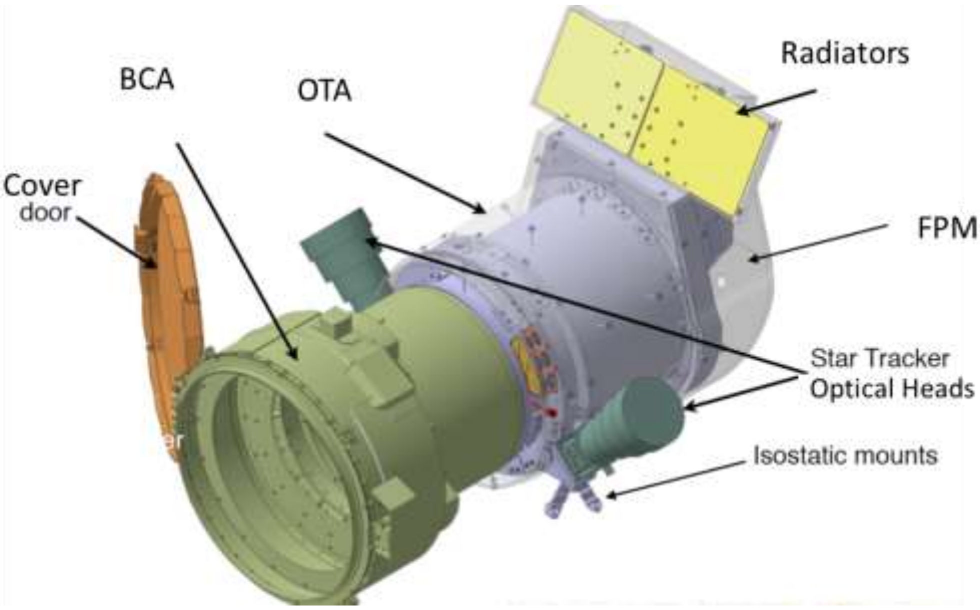

Figure 3: CHEOPS instrument configuration (courtesy of University of Bern).

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4.3 The CHEOPS spacecraft

The CHEOPS spacecraft activities are led by Airbus Defence & Space (ADS) - ECE (Spain) and its design is based on the use of the AS-250 platform, an ADS product line designed for small and medium size missions operating in LEO [9]. The existing flight and design heritage has also allowed a simplification of the model philosophy, both at unit and satellite level. The S/C configuration is illustrated in Figure 4 below. It is characterized by a compact platform body, with a hexagonal-prismatic shape and body-mounted solar arrays, which also maintain in the shade the instrument and its radiators for all nominal pointing directions, within an half-cone of 60 deg centred around the anti-Sun direction.

The S/C has a compact size, with an height of just over 1.5m and a footprint remaining in a circle with a 1.6 m radius. The total wet-mass is close to 290 kg (including 5% system level margins retained at CDR). Such dimensions and mass are in line with the key requirement of maintaining compatibility with different small and medium size launcher vehicles as an auxiliary or co-passenger. More specifically, the S/C configuration has been optimized to be compatible with the ASAP-S and VESPA adapters for a shared launch respectively on Soyuz or VEGA. In fact the S/C is designed to be compatible with launch environment requirements enveloping different launchers, including also Falcon-9.

The hexagonal-prismatic platform features vertical beams, corner joints and lateral panels which can be opened to facilitate the equipment integration (Figure 4, right side). The three lateral panels in the anti-Sun direction are equipped with radiators procured from Iberespacio (ES).

The key avionic units (On-Board Computer, Remote Interface Unit, Power Control & Distribution Unit) and On-Board Control Software are inherited from the AS-250 product line. Part of the AOCS equipment also belongs to the AS-250 line, with the exception of the reaction wheels (provided by MSCI, CA), the absence of a Coarse Sun Sensor and the down-scaling of the magneto-torquers (Zarm, DE). The two Hydra star trackers are provided by Sodern (FR) and installed on the instrument optical telescope assembly to minimize misalignment to the instrument LoS induced by thermo-elastic distortion.

The electrical power is provided by 3 solar arrays, two lateral panels and a central one. The total geometric area is about 2.5 m^2. The Photo-Voltaic Assembly (Leonardo, IT) is based on 3G30 solar cells, which are installed on 3 sandwich panels with a CFRP skin; the assembly is sized for an average power of just below 200 W (in nominal mode).

The CHEOPS spacecraft includes a compact, mono-propellant Propulsion Module (PM) from Astrium-ST (DE), inherited from the Myriade Evolution design and including an Hydrazine tank with a capacity of 30 litres (Rafael, IS), 4 small 1N thrusters and associated piping and valves. The PM has been assembled and tested as a separate sub-system before integration on the satellite.

The telecom sub-system is based on a redundant S-band transceiver (Honeywell, formerly COM DEV UK), with two sets of RX and TX antennas (located respectively at the +Z and –Z end of the S/C – see figure 4).

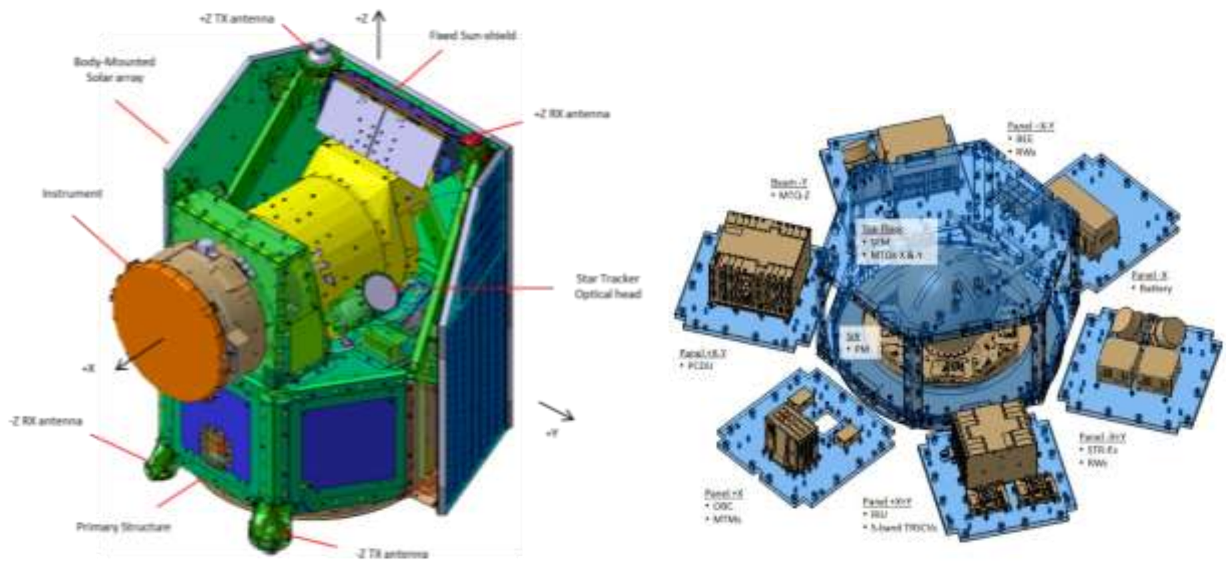

Figure 4: CHEOPS spacecraft configuration and units accommodation in the platform

(courtesy of ADS-ECE).

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4.4 The CHEOPS Ground Segment

The CHEOPS Ground Segment (GS) is based on the Mission Operation Centre (MOC) located at Torrejon de Ardoz (INTA, ES), the Science Operation Centre (SOC) at University of Geneva (CH) and two Ground Stations (G/S) located respectively at Torrejon and Villafranca (ES). A third G/S, located in Kiruna, is provided by ESA for use during LEOP. All operations, including LEOP and commissioning, are executed from the MOC. The Mission Planning System is under SOC responsibility.

The CHEOPS Ground Segment and operational concept reflect the fast-track and low-cost nature of the mission, following two basic principles: 1) maximum reuse of existing infrastructure and operational tools, 2) high levels of both on-board autonomy and automation in the operations, in order to minimize the required manpower.

The CHEOPS operational concept does not foresee stringent requirements in terms of orbit control, thus facilitating flight dynamics activities. In particular, after the initial launcher dispersion correction manoeuvre performed in LEOP, no orbit maintenance manoeuvres are required, with the LTAN remaining within the allowed range for the duration of the nominal mission. The orbit determination requirements can be fulfilled via TLE (Two Line Elements); Doppler measurements will also be used as backup and to improve the orbit determination accuracy if needed. The satellite does not have a GPS receiver on-board and the state vector and the OBC-UTC time correlation coefficients will be computed on ground and uplinked periodically to the spacecraft.

The Science Operations Centre (SOC) is responsible for mission planning, producing a weekly activity plan (with a sequence of inertial pointing directions and associated instrument parameters for each observation). The activity plan will be sent to the Mission Operations Centre (MOC) to verify that no critical spacecraft constraints are violated and to be converted to telecommands and uplinked to the spacecraft for execution in the mission timeline (MTL). The sequence of ground passes (typical for a dawn-dusk SSO) includes 5 to 6 daily passes over the G/S of Torrejon (or Villafranca, since the MOC plans to use both of them depending on their availability). Each pass has a duration of 7 to 10 minutes and 2 to 3 of these passes take place in the early morning (around 7 a.m. local time) and 2 to 3 passes in the early evening (around 8 p.m. local time). All passes will be used to downlink the spacecraft TM at a fixed downlink rate of 1143 Kbps, compliant with the daily instrument data generation of 1.2 Gb. It is planned to use one pass per week to uplink the activity plan to the satellite MTL. A high degree of automation has been implemented in the Mission Control System (MCS) and the MOC, so that nominally only the uplink passes will require the presence of the operator.

The Kiruna ground station will be used during LEOP to complement the Torrejon and Villafranca stations, providing additional passes (typically up to 10 per day) and enabling an earlier acquisition of the spacecraft after the separation from the launcher. The nominal duration of the LEOP is 4 days, concluding when the spacecraft is safely in the nominal operational orbit and ready for starting payload operations. A two month In-Orbit Commissioning (IOC) phase will follow, before the start of the nominal science operations.

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5. Development activities

5.1 Instrument test campaign

A instrument structural and thermal model has been assembled with objectives of verify and train complete integration of the instrument including MLI, seal between OTA and BCA and star trackers dummies, perform a thermal balance test and thermal vacuum cycling of the complete instrument, verify mechanical interfaces with the platform by mating it with the platform top floor, undergo mechanical campaign at spacecraft level (sine, acoustic, shock) and verify correct opening of the cover after test campaign

A dedicated thermal chamber was procured by the University of Bern (as shown in the following figure) for the thermal test which has also been used for the calibration of the instrument flight model, as shown in the figure below.

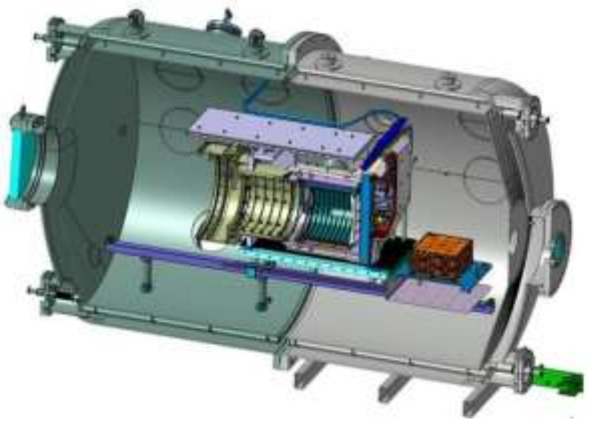
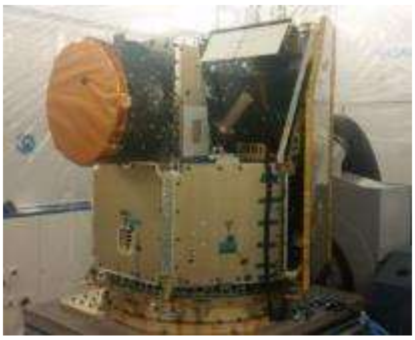


Figure 5: Thermal vacuum chamber set up at UBE (left) , flight model installation (right)

The thermal balance test has allowed to correlate the thermal model. A total of six thermal balance case have been run and the temperature readings have been compared to the thermal predictions from the thermal model. Using the correlated model temperature and heating power maps have been computed. The results show that for all the available pointing attitudes the stability requirements for CCD (10mK) and FEE (50mK) are respected. For the cold case when the radiators receive the lowest external heat load the computed stability of CCD and FEE is well within the requirement.

The instrument STM has then been delivered to the spacecraft contractor (ADS) to undergo a complete mechanical campaign. The levels seen at spacecraft level have been compared to the test levels at unit level and it has been shown that the unit test specification covered with margin the spacecraft specification. Following system level test a relaxation of the mechanical environment has been granted. A dedicated clamp band test at spacecraft level allowed to have confidence in the instrument design, particularly for the unit sensitive to shock such as the main mirror which is made of Zerodur.



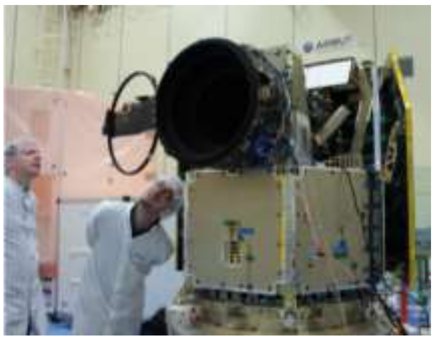


Figure 6: Spacecraft SQM model during sine vibration test (left) SQM during acoustic test (center) opening of the cover following mechanical test campaign (right)

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Following the completion of the SQM test the instrument flight model has been built, assembled and tested. For the vibration test the shaker facility at University of Bern was used, particular care was used to comply with the cleanliness requirement and to reduce to the minimum particle contamination during environmental campaign.

5.2 Instrument performance and calibration campaign

Following the delivery of the integrated telescope from Leonardo in May 2017 and the availability of the FPM EM, EQM and then FM, the alignment campaigns could take place as shown in the figure below. A dedicated calibration bench was provided by the University of Genève as described in [11] and modified for the instrument alignment. Lessons learned from the alignment with FPM EM/EQM were implemented for the alignment of the FPM FM allowing to reach the required PSF size in vertical configuration and then to verify it in horizontal configuration during TV and calibration test. In particular improvement were made on the apodizer to increase the uniformity of the source illumination and to the set up to position the FPM.

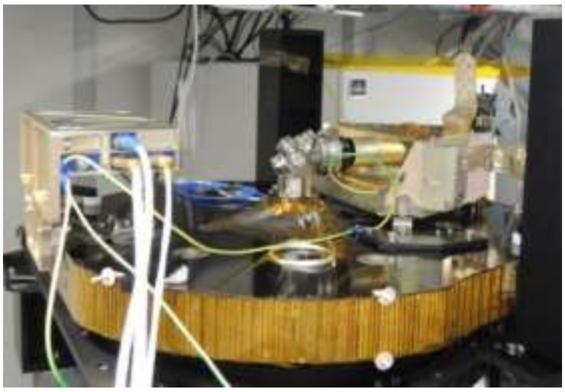

Figure 7: Cheops telescope with FPM EM/EQM/FM during alignment (left) Focal plane module EM/EQM mounted and aligned on optical bench (right)

The PSF was characterized using red light and white light and the measured PSF was used in simulation to derive the noise induced by the jitter of the satellite and the flat field, which was also measured as part of the calibration. The result show compliance to the requirement of less than 5ppm during observation period.

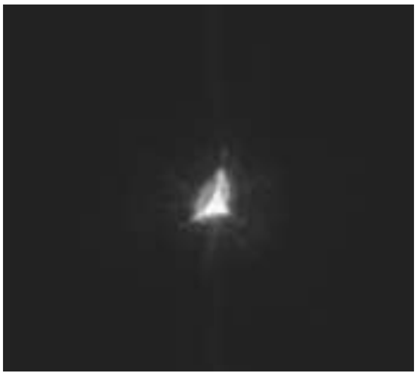

Figure 8: Cheops PSF size and shape as measured with monochromatic light at operating condition (in a logarithmic scale without corrections)

The PSF trefoil shape is a consequence of the primary mirror mounting which needed to be introduced in order to sustain the high launch loads. The shape however has been taken into account in the noise calculations and found to have minor impact on the performance figures.

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Extensive calibration was performed to derive the bias reference pictures at nominal operating conditions for the nominal and redundant channel, the gain and gain sensitivity to bias voltages and temperature variations. Calibration measurements were also done varying the temperatures of the CCD and of the front end electronic around the nominal temperature settings.

All read out mode were exercised: faint, bright and ultra-bright star. The bias voltage settings of the CCD were optimized to have larger full well possible.

The stability measurement was found very challenging due to the extreme sensitivity of the instrument and the difficulty in maintaining the light source stable to the ppm level for long times. The results indicate that the variation in the flux is not due to the instrument instability but to the lab environment and source stability.

Overall the calibration and performance campaign gave confidence that the instrument noise budget can be achieved. Further information can be found in [8].

5.3 Platform and satellite activities

The platform and satellite activities progressed at steady pace with the system SRR in March 2014, selection of ADS-ECE as prime contractor in April 2014, system PDR in September 2014 and the system CDR in May 2016.

In September 2015, the platform Structural Qualification Model (SQM), consisting of the flight structure and equipment mass dummies, was mated with the instrument STM, marking the start of the satellite structural model test campaign. The mechanical test campaign was successfully completed in November 2015, after quasi-static, sine, acoustic and shock tests (see figure 7).

At the beginning of 2016 the platform SQM was then refurbished into the flight structure and the integration of the flight equipment started. In May 2016, following the delivery of the instrument EM and of a new release of the on-board software, the satellite EFM campaign was completed, with the verification of the electrical and software interfaces between platform and instrument. Delta-qualification activities required for the solar arrays and the S-band transponder were then performed and completed beginning of 2017.

The platform activities related to functional verification and tests of the platform equipment have been completed by July 2017. Following the delivery of the instrument in April 2018 the overall satellite has been submitted to a complete environmental test campaign, mechanical thermal and EMC.

In parallel negotiations with Arianespace for the procurement of a shared flight opportunity as a co-passenger on Soyuz from Kourou have been concluded and a launch window has been agreed for November 2019.

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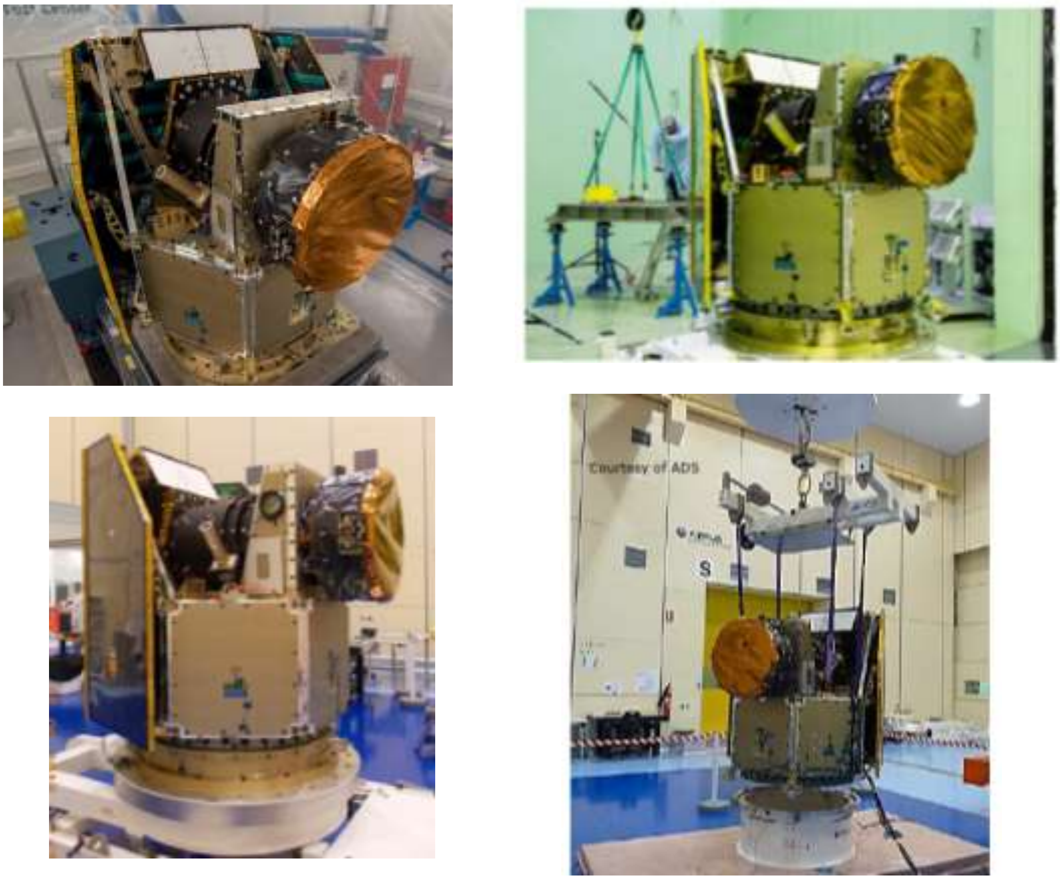

Figure 9: Top left Satellite Structural Model (STM) undergoing vibration tests (courtesy of RSSZ-CH), top right during acoustic test at ESTEC (courtesy of ETS), bottom left during mass measurement and bottom right during shock test (courtesy of ADS Spain).

Figure 10: CHEOPS flight model during the integration phase (courtesy of ADS Spain).

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5.4 Ground Segment activities

The development of the CHEOPS Ground Segment has followed an approach in line with the low-cost and fast-track nature of the project, of re-using as much as possible existing infrastructure and tools.

Mission Operation Centre located in Torrejon de Ardoz (ES) is provided by CDTI and was agreed following the selection of ADS Spain as S/C prime. This enabled to exploit major commonalities with the Seosat-Ingenio operation centre and existing operational tools. Mission Control System (MCS) and Satellite Simulator (SatSim) were adapted by GMV-ES, under contract by ESA, in the frame of ESA contribution to the Ground Segment.

The MOC Requirements Review was held in May 2014, followed by the Ground Segment PDR closed in June 2015, the CDR in January 2016, and the Ground Segment Implementation Review in June 2017. The first System Validation Test (SVT-0), aimed at verifying interfaces between the MCS and the platform, was performed in February 2016 using the platform EFM and the first release of the CHEOPS Mission Control System. The second System Validation Test (SVT-1A), dedicated to the validation of the platform basic operations, was performed in June 2017 with the platform PFM, to be followed by a complementary test (SVT-1B) focused on the instrument operations and planned for mid-October 2017. End-to-end operational scenarios for LEOP, IOC, and the science routine operations phase (thus including both SOC and MOC) will be validated during SVT-2 and SOVT (System Operations Validation Test), which are already defined and scheduled to be performed in 2018.

In March 2016 the first Radio Frequency Compatibility Test (RFCT1), aimed at verifying interfaces between the satellite telecom sub-system and the ground antenna, was conducted at Torrejon (figure 8 – left side), while a second test (RFCT2) was performed at ESOC to confirm compatibility with the ESA ground station network at the end of June 2016.

The integration of different operational tools (MCS, SatSim, Flight Dynamic Tools) in the first version of the CHEOPS operation control system was completed in July 2016 (figure 9 – top right); the first integrated SOC was ready for initial GS-level test in March 2017. Final versions of MOC and SOC has been delivered for the Ground Segment Readiness Review, end 2018. This review has marked the start of the simulations campaign, to train training the Mission Control Team for the LEOP, IOC, and science routine operations phases.

Figure 11: Left side: the Ground Station in Torrejon de Ardoz used for CHEOPS; right side - top: MOC control room at Torrejon de Ardoz (courtesy of INTA-ES); right side – bottom: SOC building in Geneva (courtesy of Univ. of Geneva, CH).

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6. Conclusion

As the first small mission (S-mission) in ESA's Science Programme, CHEOPS is truly a pathfinder with a tight schedule and complex technical and programmatic challenges.

After successful PRR and SRR in 2013, PDR in July 2014, a complete instrument STM has been built and tested at instrument and spacecraft level, including a challenging instrument structure stability test. This has provided confidence in the design allowing to conclude successfully the instrument CDR by mid-2016.
Three test campaigns performed with the CIS EM/EQM in April 2016 and September/October 2017 allowed to verify the electrical, SW and AOCS interfaces ahead of the flight instrument integration.
Instrument flight model has been built, tested and calibrated showing performances in line with the requirements. The Cheops instrument has been shipped to the spacecraft prime contractor for integration on the platform in April 2018. Following the instrument delivery the entire satellite has been submitted to an extensive environmental test campaign.

The Cheops satellite is now ready for a dual launch on board Soyuz from Kourou planned for November 2019.

The authors acknowledge the great dedication of the Cheops instrument and satellite team thanks to which it was possible to reach the satellite readiness milestone.

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