CHEOPS: the ESA mission for exo-planets characterization ready for launch.

J. Asquier(1), N. Rando(1), C. Corral Van Damme(1), F. Ratti(1),
K. Isaak(1), R. Southworth(2), F. Safa(1), C. Broeg(3), T. Beck(3),
W. Benz(3), A. Borges(4), D. Cortes(4), and R. Palacios(4)

(1) ESTEC, European Space Agency, 2200 AG,
Noordwijk, NL,
(2) ESOC, European Space Agency, 64293,
Darmstadt, DE
(3) Center for space and habitability, University of
Bern, 3012 Bern, CH
(4) Airbus Defence & Space, Avenida de Aragon 404,
28022, Madrid, ES

ABSTRACT

The European Space Agency (ESA) Science Programme Committee (SPC) selected CHEOPS (Characterizing Exoplanets Satellite) in October 2012 as the first Small-class mission (S1) within the Agency's Scientific Programme. It is considered as a pilot case for implementing "small science missions" in the agency with the following requirements: science driven mission selected through an open Call; an implementation cycle, from the Call to launch, drastically shorter than for Medium-class (M) and Large-class (L) missions; a strict cost-cap to ESA, with possibly higher Member States involvement than for M or L missions.

The CHEOPS mission is devoted to the characterization of known exoplanets orbiting bright stars, achieved through the precise measurement of exoplanet radii using the technique of transit photometry. It was adopted for implementation in February 2014 as a partnership between the ESA Science Programme and Switzerland, with a number of other Member States delivering significant contributions to the instrument development and to operations.

The CHEOPS instrument is an optical Ritchey-Chrétien telescope with 300 mm effective aperture diameter and a large external baffle to minimize straylight. The compact CHEOPS spacecraft (approx. 300 kg, 1.5 m size), based on a flight-proven platform, will orbit the Earth in a dawn-dusk Sun Synchronous Orbit at 700 km altitude. CHEOPS completed the Preliminary Design Review at the end of September 2014, and passed the Critical Design Review in May 2016. In the course of 2017, flight platform and payload have been integrated and tested, and then followed by satellite level activities, targeting flight readiness by the end of year 2019. Implementation and validation of the ground segment, which is composed of the MOC (Mission Operations Centre), located in Torrejón (Madrid, Spain) and the SOC (Science Operations Centre), located at the University of Geneva (Switzerland) was achieved in parallel. CHEOPS will be launched as a secondary passenger on a Soyuz from Kourou by end of 2019.

The paper describes the latest CHEOPS development status, focusing on the activities for verification and validation of the satellite and the system at large, including the ground segment and the activities in preparation for S/C launch and its operations. Additional details can be found on the ESA and UBE websites referred in [8].

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 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, see [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 by the end of 2018 the satellite level tests, including the environment campaign and functional / system tests, were completed. In February 2019, the System Qualification and Acceptance Review (S-QAR) was concluded and to date the project has demonstrated launch readiness both for the space and ground segment. Currently the launch aboard Soyuz, together with COSMO-SkyMed, is expected by mid-November 2019.

Additional information with respect to the project definition and organisation, mission requirements, challenges can be found in [2] and [3].

2 - Mission description summary

Figure 1 illustrates the mission architecture of CHEOPS.

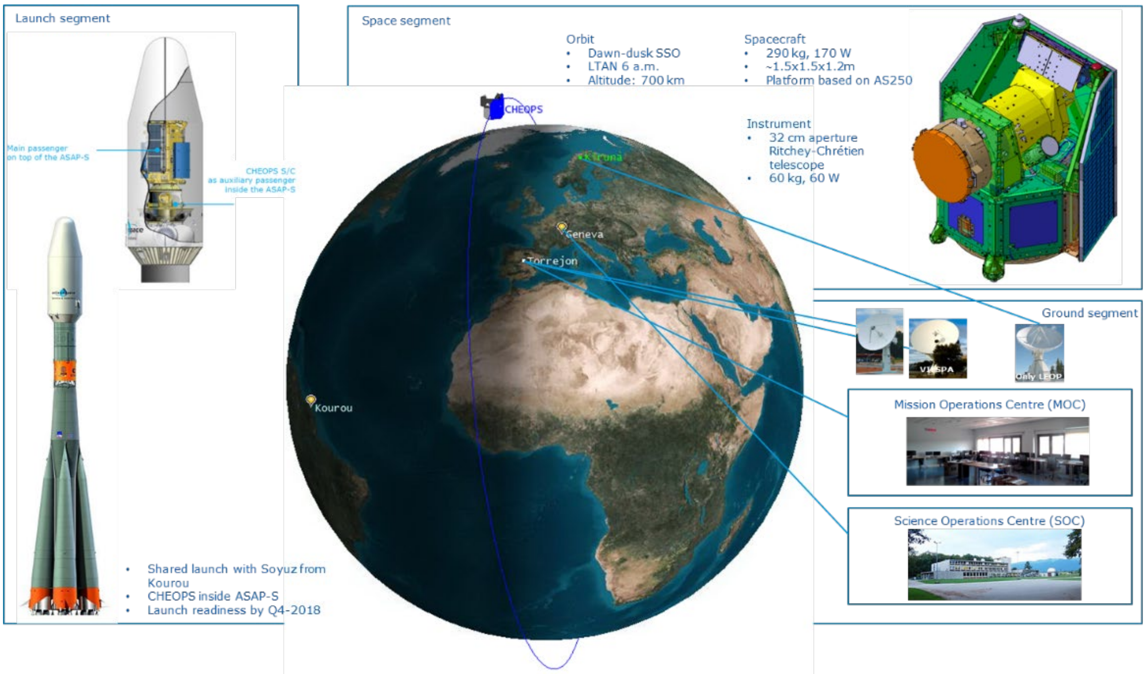

Figure 1 – Overview of the CHEOPS mission

2.1 - Space segment design summary

The CHEOPS space segment consists of a spacecraft (S/C) based on the use of the AS-250 platform, an Airbus Defence & Space (ADS) product line, designed for small and medium size missions operating in LEO. The existing flight and design heritage has also allowed a simplification of the model philosophy (see section 3), both at unit and satellite level. The S/C configuration is illustrated in Figure 2. It is characterized by a compact platform body, with a hexagonal-prismatic shape and body-mounted solar arrays, which also maintains in the shade the instrument and its radiators for all nominal pointing directions, within a half-cone of 60 deg centred around the anti-Sun direction.

The S/C has a compact size, with a height of just above 1.5m and a footprint remaining in a circle with a 1.6 m radius. The total wet-mass is equal to 272.1 kg. It was designed to be compatible with launch environment requirements enveloping Soyuz, VEGA and Falcon-9 launchers. But more specifically, the S/C configuration had been optimized to ASAP-S adapter for a shared launch on Soyuz.

The selected orbit is a dawn-dusk, Sun-Synchronous Orbit (SSO), with an altitude between 650 and 800 km for design flexibility and a nominal operational phase of 3.5 years. The selected baseline is an altitude of 700 km.

The AOCS design, using information from the instrument (payload-in-the-loop), allows to maintain the commanded pointing direction, 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 (see Figure 3).

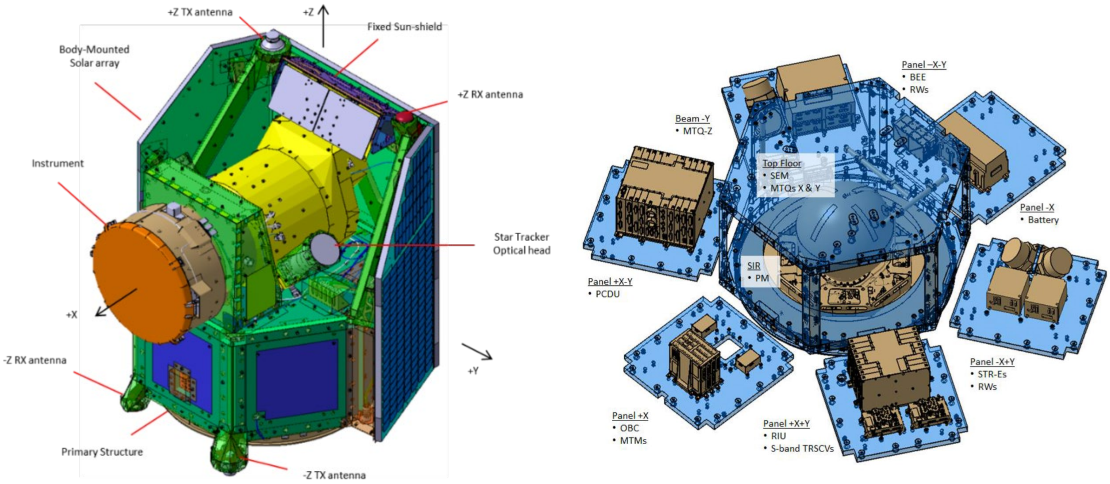

Figure 2 – CHEOPS S/C configuration (left) and units' accommodation in the Platform (right) – Courtesy of ASE.

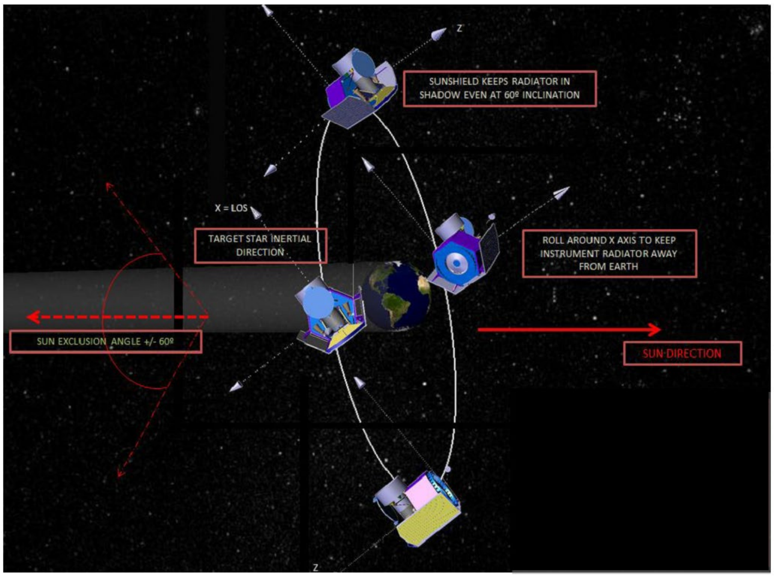

Figure 3 – CHEOPS spacecraft attitude and pointing directions in the operational orbit

The CHEOPS instrument is a high precision photometer operating in the VIS and NIR range (0.4 to 1.1 um). It has a total mass of approximately 60 kg and a power budget of about 55 W and was developed by a consortium of institutes led by the University of Bern (CH). ESA has also contributed with the procurement of the focal plane detector. The instrument is composed of following 4 main units:

- **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.
- **Optical Telescope Assembly (OTA)**, including an on-axis, Ritchey-Chretien telescope with a clear aperture diameter of 30 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 -20C. These operating temperatures are achieved by means of two dedicated radiators, both protected by the S/C Sun-shield.

- **Sensor Electronic Module (SEM)**, with the function of controlling the FPM and accommodated as a separate unit inside the platform.
- **Back-End Electronics (BEE)**, providing overall instrument control and including Data Processing Unit and Power Supply and Distribution Unit.

Both the BEE and SEM are installed inside the platform. Figure 4 provides an overview of the CHEOPS Instrument configuration and a schematic of the electrical I/F between CHEOPS Platform and CHEOPS Instrument.

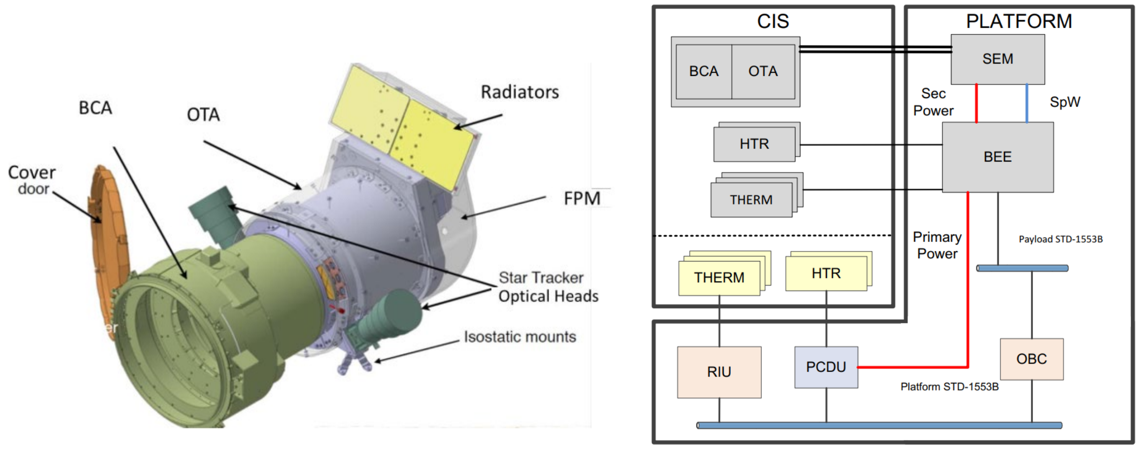

Figure 4 – CHEOPS Instrument configuration (left – Courtesy of UniBern) and schematic of the electrical I/F between the Platform and the Instrument (right – Courtesy of ASE).

The S/C activities are led by Airbus Defence & Space (ADS) - ASE (Spain), including integration of the Instrument. Additional information on the CHEOPS Platform and Instrument can be found in [4] and [5].

2.2 - Ground segment design summary

The CHEOPS Ground Segment (GS), see photos on Figure 5, is constituted of the:

- Mission Operation Centre (MOC) located at Torrejon de Ardoz (INTA, ES),
- Science Operation Centre (SOC) at University of Geneva (CH),
- 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. Since the satellite does not have a GPS receiver on-board, the state vector and the OBC-UTC time correlation coefficients will be computed on ground and uplinked periodically to the spacecraft.

The 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 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 5 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.

Figure 5: 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).

3 - Verification approach

In line with the mission and different segments/systems shortly presented, a dedicated verification approach was setup with the objectives to:

- qualify the design and demonstrate that the design of the S/C and units is robust enough to comply to the requirements with adequate margin, e.g. when applying environmental conditions more severe than the hardware will experience during flight,
- ensure that the flight S/C in agreement with the qualified design, is free from workmanship defects and acceptable for use,
- verify that the S/C is compatible with the selected launcher, MOC and SOC,
- confirm the S/C functionality after launch to complement the on-ground verification allowing demonstration of compliance for those requirements that can only be verified in flight.

The main drivers for the defined verification approach were based on:

- selection of the requirements to be verified and the CHEOPS programme constraint for having the S/C ready for launch by end 2018 / early 2019,
- early verification of the heritage at platform unit level to confirm their qualification w.r.t. CHEOPS environment/use conditions with definition of punctual delta qualification,
- completed qualification and acceptance cycle for the instrument accounting for the specific design and limited heritage at unit level,
- Platform Functional Chains test specification and test procedures re-used from already developed S/C based on AS250 with adaptations for CHEOPS specificities when necessary,
- verification of the instrument and the platform performed as independently as possible,
- instrument functional verification at S/C level focussed on instrument interfaces verification and functional testing. Instrument optical performances not verified at satellite level, only health check.

Accounting for the above, the following model philosophy was established:

- **CHEOPS Structural Qualification Model (SQM)**: composed by the Platform Structural Qualification Model (SQM) and the Instrument Assembly Structural and Thermal Model (STM)
- **CHEOPS Electrical and Functional Model (EFM)**: composed by the Platform Electrical and Functional Model (EFM) and the Instrument Assembly Engineering Model (EM)
- **CHEOPS Electrical Hybrid Model (EHM)**: composed by the Platform Proto-Flight Model (PFM) and the Instrument Assembly Electrical Qualification Model (EQM)
- **CHEOPS Proto-Flight Model (PFM)**: composed by the Platform Proto-Flight Model (PFM) and the Instrument Assembly Proto-Flight Model (PFM)

This model philosophy and transitions (see Figure 6) allowed for an independent verification of both Instrument and Platform as stand-alone parts. In addition, with this approach, the instrument models set the tone for the satellite verification, i.e. the platform models were made ready with enough margins in order to maintain the tight schedule.

In order to support the verification of the Radio Frequency compatibility between the S/C and the CHEOPS ground segment, a representative RF suitcase was adapted to integrate the Honeywell S-band Transceiver EM and to perform Radio-Frequency Compatibility Tests (RFCT).

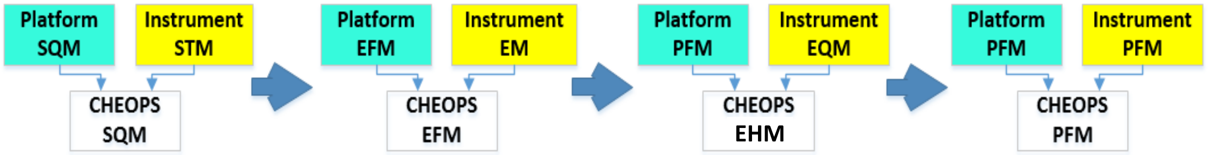

Figure 6 – Model philosophy transitions during the CHEOPS development.

3.1 - CHEOPS SQM

The CHEOPS SQM aimed at:

- demonstrating the mechanical qualification of the S/C design and in particular, the mechanical interfaces between Instrument and Platform for an envelope of specified qualification loads (e.g. sine, acoustic and shock) for launchers' envelop,
- demonstrating the structure qualification,
- validating the Mechanical Mathematical Models, correlation of model prediction with test results,
- confirming the mechanical loads derived to subsystem and units, which for the instrument was of utmost importance for adjusting the qualification and acceptance envelop,
- validating the integration and alignment procedures of the Instrument.

It was composed of the:

- Platform structure (refurbished for the CHEOPS PFM following the SQM test campaign),
- Solar Arrays panels substrate flight hardware equipped with mass dummies for the cells and harness to be representative in terms of mass properties and stiffness. following the SQM campaign the panel were refurbished for the CHEOPS PFM,
- Propulsion Module mechanically representative (dummy tank and dummy units attached to flight representative baseplate),
- Platform units, including harness, mass and CoG representative,
- Instrument STM.

Finally, the qualification loads for the S/C SQM test campaign (i.e. acoustic, sine and separation shock) were established as an envelope of the different flight limit loads and qualification factors specified by the selected launchers' user manual. The following mechanical test with qualification levels and durations were performed on the CHOPS SQM for mechanical qualification:

- Sine vibration test: executed in three axes and in several steps (Quasi-static loads being applied in a specific run of the sine tests),
- Acoustic test: executed in several steps,
- Launch vehicle separation shock test (performed with a clamp-band release test as sizing event).

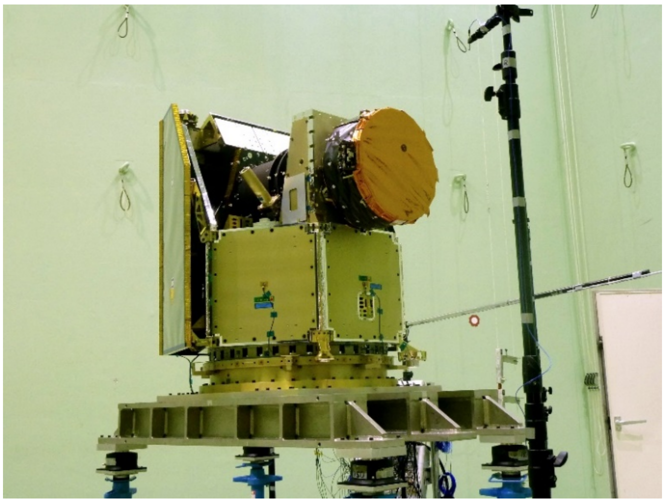

Figure 7 – CHEOPS SQM at ESTEC during the acoustic test.

3.2 - CHEOPS EFM

The CHEOPS EFM aimed at:

- validating specific adaptations for the CHEOPS mission: platform equipment selected outside the AS250 catalogue leading to modification (HW or SW), interface with the instrument (from an electrical and functional point of view), critical AOCS mode. More specifically this allowed the:
    - verification of HW and SW software interfaces and functionalities for the MSCI Reaction Wheels and Honeywell S-band Transceiver,
    - verification of the Instrument electrical compatibility with the Platform,
    - verification of the S/C harness,
    - validation of the modifications of the on-board software done for CHEOPS (non-regression tests for recurrent SW applications and validation of new SW functions),
- validating instrument critical SW interfaces with the platform (e.g. Milbus communication protocol, real time fine pointing telemetry or heartbeat),
- testing and validating the MCS – S/C TMTC interfaces as part of the first System Validation Test (SVT-0) and validating a first set of Flight Operation Procedures (FOPs),
- debugging and validating AIT procedures and associated material modified or defined for CHEOPS mission needs in order to de-risk the PFM campaign.

It was composed of the:

- main platform units (EQM models and simulators for non-critical or non-complex units). For the RW and the TRCV, one FM model was also integrated in a second step.
- instrument EM composed of the BEE EM, SEM and FPM simulator), including early version of the instrument embedded software.
- on-board software in the OBC including all functionalities (AS250 generic and modified ones).

Platform units and instrument units were installed on a support structure (Flat-Sat) in which the EM harness was also routed (see Figure 8).

Figure 8 – Subset of the CHEOPS EFM (w/o Instrument EM – courtesy of ASE).

3.3 - CHEOPS EHM

The CHEOPS Electrical Hybrid Model (EHM) aimed at:

- validating all instrument SW interfaces with the Platform and commanding of the Instrument,
- testing and validating the Platform and Instrument basic operation as part of the second System Validation Test (SVT-1A and -B),
- validating a second set of FOPs.

Figure 9 shows this model, with emphasis to the Instrument EQM interfacing with the Platform PFM.

Figure 9 – CHEOPS EHM (focus I/F with Instrument EQM) – courtesy of ASE

3.4 - CHEOPS PFM

The CHEOPS PFM is composed of all the Platform flight hardware and the Instrument Assembly flight hardware. It was submitted to a proto-flight test campaign allowing the completion of the qualification programme for those aspects not covered by the SQM and EFM and the acceptance of the satellite before flight. This consisted in a complete environmental campaign (including vibration, acoustic, launcher fit check and separation test, thermal balance and thermal vacuum, EMC and RC compatibility).

However prior being submitted to the environmental campaign, the Platform PFM and the complete CHEOPS PFM underwent a series of System functional verification in order to:

- exercise all flight units ensuring that all equipment redundancies are covered,
- prove that tests on both EFM and PFM deliver identical results,
- validate the workmanship of the CHEOPS PFM through well-known tests cases.

The process, with the already performed tests, is summarized in Figure 10 below.

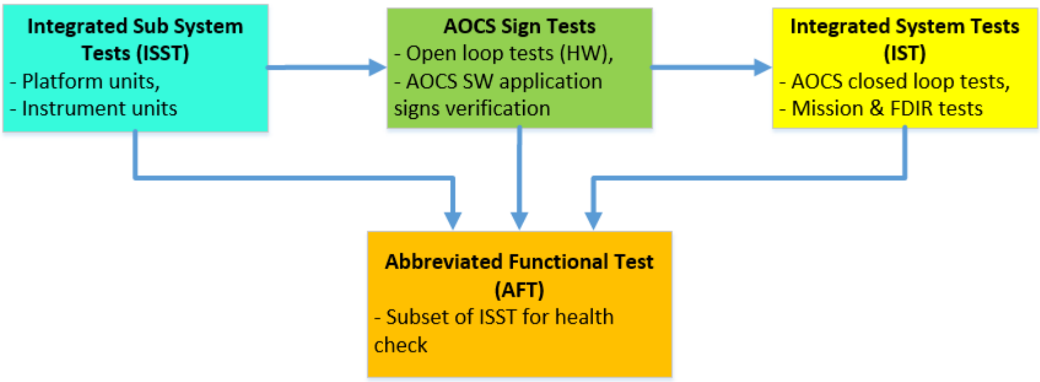

Figure 10 – CHEOPS System Functional Verification approach

The objectives and scope of the tests were further elaborated as follows:

- **Integrated Sub System Tests (ISST)**: Reference tests to validate the good functioning of each functional chain at the beginning and at the end of the S/C AIT sequence. All physical links and hardware TM and TC are verified mostly by the means of automated tests sequences. Tests are organised by subsystems (EPS, DHS, AOCS, Propulsion, S-band, Thermal and Instrument) and are carried out in different configurations so that every link is checked, including cross-strappings.
- **AOCS Sign Tests:** Tests aim at verifying the sign of all sensor-to-actuator functional strings. They are performed in different steps and consist in verifying that the actuator output sign is consistent with the sensor input sign given the attitude control law that is involved.
- **Integrated System Tests (IST)**: Tests to verify the satellite behaviour in system and flight representative conditions. They are structured according to the flight operation phases (in nominal and failure conditions), to address mission and FDIR tests. The sub-systems are checked, as much as possible, in end-to-end configuration (for example AOCS in closed loop including Instrument in the AOCS loop mode). ISTs focus on maximum coverage of hardware functions and interfaces (including artificial scenarios to generate errors) and are representative of the system mode transitions, safe / survival mode or even complete mission phases like Launch and Early Orbit Phase (LEOP) and nominal operations.
- **Abbreviated Functional Test (AFT)**: Subset of the ISST to verify the integrity of the functional chains of the S/C, in order to confirm the success of the previous AIT phase or transport and to prove that no damage of any chain occurred.

To finalise the Ground Segment compatibility verification and the validation of the complete set of FOPs, additional SVTs were defined and performed, with main objectives as follows:

- **SVT-2/SOVT**: to confirm Ground Segment end-to-end TM/TC operational chains (external MCS interfaces including interfaces between MOC and SOC) in close loop with the real S/C, including the training of CHEOPS operations team,
- **SVT-3**: to confirm the MOC configuration status for LEOP.

Finally, following LEOP, in orbit verification will be performed including activities such as to:

- verify all functions and ensure that no degradation occurred during the launch,
- perform calibration (e.g. Star Tracker optical heads alignment)
- complete the demonstration of CHEOPS S/C performance.

4 - Activity status

4.1 – Instrument activities

The CHEOPS Instrument development started almost immediately after the proposal selection, at the end of 2012, thus approximately 9 months ahead of the start of the platform and spacecraft level activities.

The instrument Structural Thermal Model (STM) was completed in early 2015 and has undergone a dedicated mechanical and thermal campaign, which was completed in August 2015. This model was then delivered to the S/C contractor for the CHEOPS SQM campaign.

The telescope flight structure was subject in June-July 2015 to dedicated thermal stability tests with the objective to accurately measure the inter-mirror distance at different temperatures, which was found to be compliant to the CHEOPS stringent stability requirement.

The Instrument EM, with an intermediate control software version, was delivered to the S/C prime in early April 2016 for testing on the CHEOPS EFM, allowing the verification of electrical and critical SW interfaces between platform and instrument.

The Instrument EQM, with an almost final control software version, was delivered to the S/C prime in February 2018 for testing on the CHEOPS EHM, allowing the verification of electrical and SW interfaces between platform and instrument and performing dedicated SVT.

Finally, the flight Instrument (PFM model) was built, tested and calibrated showing performances in line with the requirements. It was shipped to the spacecraft prime contractor second week of April 2018 for incoming inspection and integration as part of the CHEOPS PFM.

Figure 11 provides a photo of the CHEOPS Instrument bagged during incoming inspection in ASE Madrid.

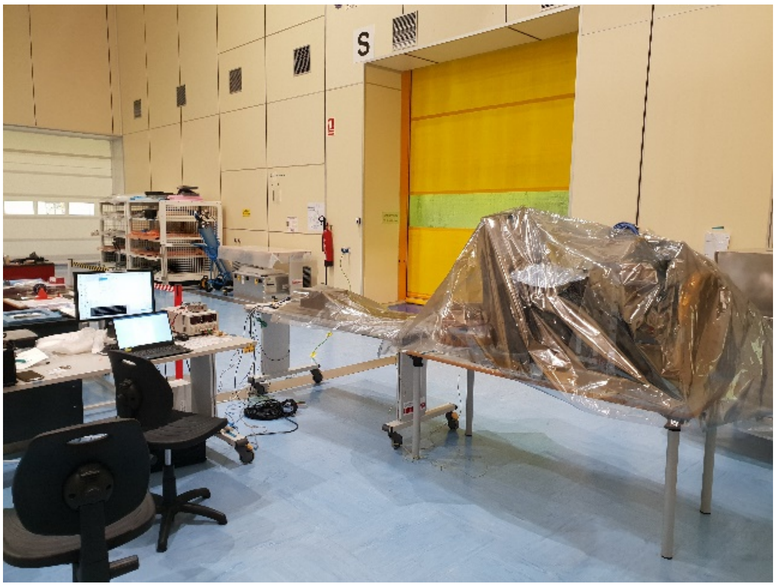

Figure 11 – CHEOPS PFM Instrument at ASE – courtesy of ASE

Additional details w.r.t. the CHEOPS Instrument development and verification campaign are provided in [6] and [7].

5.2 - Platform and S/C 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 SQM 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.

At the beginning of 2016 the platform SQM structure 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 CHEOPS EFM campaign was completed.

Delta-qualification activities required for the solar arrays and the S-band transponder were completed beginning of 2017. The equipment procurement activities were completed with the battery delivery and all units were mechanically and electrically integrated on board the platform by mid-2017.

All platform test and verification activities were finalised in early 2018. The Instrument PFM was mechanically and electrically integrated on the Platform end of April 2018. Environmental verification activities at CHEOPS PFM level started Q3 2018, and were followed by post-environmental ISST and delta IST in order to achieve flight readiness at satellite level first quarter of 2019.

5.3 - Ground Segment activities

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

The integration of different operational tools (e.g. Mission Control System - MCS, Satellite Simulator, Flight Dynamic Tools) in the first version of the CHEOPS operation control system was completed in July 2016; the first instance of the integrated SOC was ready for initial GS-level test in March 2017. Final versions of MOC and SOC were made available before the Ground Segment Readiness Review, which took place end 2018. The simulations campaign started in early 2019, with the main objective of training the Mission Control Team for the LEOP, IOC, and science routine operations phases.

5.4 – Activity summary

Figure 12 identifies the milestones achieved and the last milestone planned until completion, i.e. the launch!

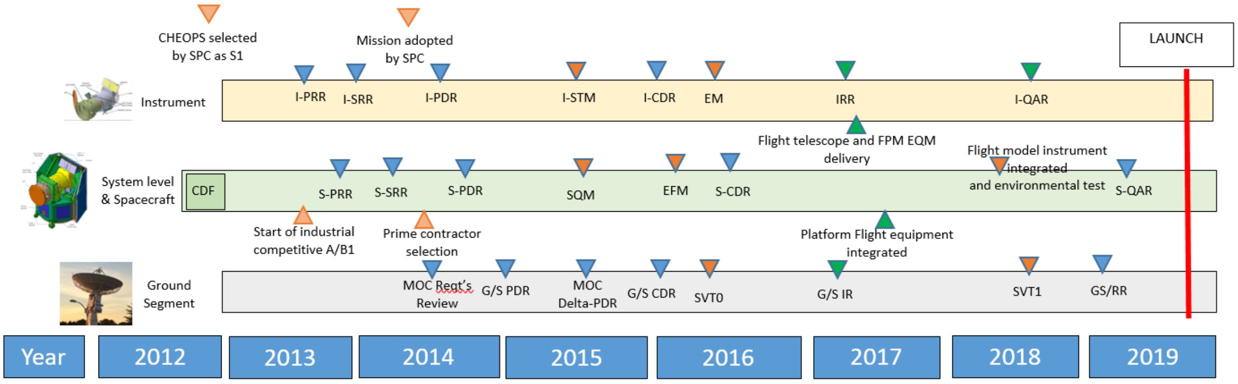

Figure 12 – Summary of the milestones achieved and planned until completion

6 - Conclusion

CHEOPS, selected by the Science Programme Committee of the European Space Agency as the first small-class mission, passed the system Critical Design Review in May 2016, less than 4 years after its selection and in less than 2.5 year from its formal adoption (February 2014). The specific project implementation approach has allowed to cope with the strict CHEOPS programmatic requirements, both in term of cost ceiling and in term of spacecraft development time.

The verification and validation activities were completed in December 2018, and concluded with a successful Qualification & Acceptance Review in February 2019, when CHEOPS project reached launch readiness. The S/C is currently under storage prior being transported to Kourou for a shared launch with COSMO-SkyMed on Soyuz, by mid-November 2019.

Additional details on the CHEOPS project can be found at http://sci.esa.int/cheops/ and https://cheops.unibe.ch/

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