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CHEOPS: a space telescope for ultra-high precision photometry of exoplanet transits

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CHEOPS: A SPACE TELESCOPE
FOR ULTRA-HIGH PRECISION PHOTOMETRY OF EXOPLANET TRANSITS

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ABSTRACT

The CHaracterising ExOPlanet Satellite (CHEOPS) is a joint ESA-Switzerland space mission dedicated to search for exoplanet transits by means of ultra-high precision photometry whose launch readiness is expected end 2017. The CHEOPS instrument will be the first space telescope dedicated to search for transits on bright stars already known to host planets. By being able to point at nearly any location on the sky, 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. CHEOPS will also provide precision radii for new planets discovered by the next generation ground-based transits surveys (Neptune-size and smaller). The main science goals of the CHEOPS mission will be to study the structure of exoplanets with radii typically ranging from 1 to 6 Earth radii orbiting bright stars. With an accurate knowledge 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 this mass range. To reach its goals CHEOPS will measure photometric signals with a precision of 20 ppm in 6 hours of integration time for a 9th magnitude star. This corresponds to a signal to noise of 5 for a transit of an Earth-sized planet orbiting a solar-sized star (0.9 solar radii). This precision will be achieved by using a single frame-transfer backside illuminated CCD detector cool down at 233K and stabilized within ~10 mK . The CHEOPS optical design is based on a Ritchey-Chretien style telescope with 300 mm effective aperture diameter, which provides a defocussed image of the target star while minimizing straylight using a dedicated field stop and baffle system. As CHEOPS will be in a LEO orbit, straylight suppression is a key point to allow the observation of faint stars. The telescope will be the only payload on a spacecraft platform providing pointing stability of < 8 arcsec rms, power of 60W for instrument operations and downlink transmission of at least 1.2GBit/day. Both CHEOPS paylaod and platform will rely mainly on components with flight heritage.
The baseline CHEOPS mission fits within the technical readiness requirements, short development time and the cost envelope defined by ESA in its first call for S-missions. It represents a breakthrough opportunity in furthering our understanding of the formation and evolution of planetary systems.

I. INTRODUCTION

The Characterising Exo-planet Satellite (CHEOPS) will be the first small mission (S-mission) in ESA's Science Programme. The main science goal of CHEOPS mission will be to study the structure of exoplanets smaller than Saturn orbiting bright stars. With an accurate knowledge of masses and radii for an unprecedented sample of planets, CHEOPS will set new constraints on the structure and hence on formation and evolution of planets in this mass range. This paper presents the mission and the definition of instrument achieved at I-PDR in July 2014.

II. CHEOPS MISSION

A. First S-Mission

CHEOPS was selected on October 19, 2012 and was adopted for implementation in February 2014 as the first S-class mission in ESA's Science Programme. The tight schedule and stringent budget envelope of small missions are extremely challenging. The constraints set by ESA and the SPC are a development time not exceeding 4 years and a total cost to be covered by ESA limited to 50 M€ with a total mission cost of approximately 150 M€. This corresponds to about 10% of the ESA budget of an M-mission and less than half the development time of an M-mission. The continuation of an S-mission line in ESA's Science programme hinges on the success of CHEOPS. [1] describes CHEOPS implementation approach and status, by focusing on

the challenges for meeting the S-class mission requirements and on the spacecraft procurement approach.

B. CHEOPS mission objectives

CHEOPS will be the first mission dedicated to search for transits of exoplanets by means of ultrahigh precision photometry on bright stars already known to host planets. 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 characterisation for exoplanets located almost everywhere in the sky. It will also provide precise radii for new planets discovered by the next generation of ground- or space-based transits surveys (Neptune-size). By unveiling transiting exoplanets with high potential for in-depth characterization, CHEOPS will also provide prime targets for future instruments suited to the spectroscopic characterisation of exoplanetary atmospheres.

Since the discovery of the first planet orbiting a star similar to the sun in 1995 [2], a large number of exoplanets (> 1000) have been discovered using ground-based detection methods. The most successful methods rely on detecting dynamical (radial velocity) or photometric (transit) perturbations on the host star induced by the presence of one or several planets. While the radial velocity method provides a lower limit on the mass of the planet, the transit method provides an estimate of the radius of the planet. Planets that are detected by both methods are particularly interesting: for these objects both mass and radius are known. From these values, a mean density can be derived and a first information on the physical nature of the planet can be obtained.

Despite two highly successful space missions dedicated to transit searches (CoRoT and Kepler) and almost two decades of high-precision radial velocity measurement campaigns, the number of exoplanets in the mass range 1-30 M_{Earth} for which both mass and radius are to a good precision known, is extremely limited. This originates from the fact that these masses cannot be measured accurately enough by current Doppler methods for most of the CoRoT and Kepler targets. They are simply too faint to allow the required precision in radial velocity to be reached. This leaves us with 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 goal of CHEOPS is to significantly increase the sample of objects for which both quantities are known. [3] describes scientific objectives and challenges for the scientific community.

C. Project organization & responsibilities

The CHEOPS Mission Consortium (CMC), led by the University of Bern (CH) is responsible for the following mission elements:
- Development, procurement, qualification and calibration of the instrument
- Provision of AIT services in support to the satellite activities
- In-orbit monitoring, calibration and evaluation of the instrument performance
- Provision of the CHEOPS ground segment, including:
  - The Ground station(s)
  - The Mission Operations Centre (MOC)
  - The Science Operations Centre (SOC)

ESA will be in charge of the overall mission architecture and is responsible for the following activities:
- Procurement of the CHEOPS Platform accommodating the Instrument assembly.
- Procurement of the instrument detector CCD.
- Integration, test and qualification of the complete satellite.
- Procurement of the mission control system, satellite and instrument simulator and any required flight dynamics system.
- Procurement of the launch opportunity and launch operations.
- LEOP and in-orbit commissioning.

II. SCIENCE REQUIREMENTS

The complete set of science requirements and their motivation can be found in the CHEOPS Definition Study Report (aka the Red Book) [4]. Here we summarize the most important ones.

A. Photometric accuracy

CHEOPS will target host stars of super-Earth exoplanets detected from the ground by means of high-precision radial velocity surveys. It will also target transiting Neptune-like planets detected from the new generation ground-based transit surveys. Additional targets will come from the TESS satellite, which will search for short

duration transits over the entire sky. To account for the particularities of the different detection methods and the size of the corresponding exoplanets, different photometric requirements have been derived.

For the detection of Earth and super-Earth planets orbiting G5 dwarf stars (stellar radius of 0.9 R_{sun}) with *V*-band magnitudes in the range $6 \leq V \leq 9$ mag, a photometric precision of 20 ppm (goal: 10 ppm) in 6 hours of integration time must be reached. This time corresponds to the transit duration of a planet with a revolution period of 50 days.

In the case of Neptune-size planets orbiting K-type dwarf stars (stellar radius of 0.7 R_{sun}) with *V*-band magnitudes as faint as *V*=12 mag (goal: *V*=13 mag), a photometric precision of 85 ppm in 3 hours of integration time must be reached. This time corresponds to the transit duration of a planet with a revolution period of 13 days.

B. Target Observability and Sky Coverage

The key to precise photometric transit measurements is to keep the noise in the measurements to an absolute minimum. Besides the noise associated with the detector itself, stray light is the main source of noise. This stray light is minimized through the design of the telescope itself, the orbit chosen, and by limiting the directions in which the telescope points in order to avoid solar light reflected by the Earth and/or the Moon reaching the detector. With the current design of the CHEOPS telescope, in order to meet the photometric requirements mentioned above, the following conditions have to be met:

- the angle between the line-of-sight and the sun must be larger than 120°;
- the angle between the line-of-sight and any illuminated part of the Earth must be larger than 35°. In addition, the target must have a projected altitude from the surface of the Earth equal or higher than 100 km;
- the angle between the line-of-sight and the Moon must be larger than 5°.

Despite these restrictions, CHEOPS being a follow-up mission with targets distributed all over the sky, it is essential to maximize the accessible sky fraction. Keeping in mind the detection biases associated with the methods providing the targets, the following requirements have been derived. For the small mass planets discovered by radial velocities, CHEOPS shall cover 50% of the whole sky for 50 (goal: 60) cumulative (goal: consecutive) days of observations per year and per target with observation duration longer than 50% of the spacecraft orbit duration (>50 min for 100-min spacecraft orbital period). This requirement results from a trade-off involving the maximum orbital period of the exoplanets we want to observe (50 day) which corresponds to a planetary orbit at the inner edge of the habitable zone of K stars.

For Neptune-like exoplanets detected from the NGTS facility located at ESO's Paranal Observatory in Chile, which itself covers only about 10% of the southern sky, the requirements can be relaxed. In this case, 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 observation duration longer than 80% of the spacecraft orbit duration (>80 min for 100-min spacecraft orbit).

C. Lifetime of the mission

Transit detection on bright stars identified by Doppler surveys will need as a minimum a total of 600 days of satellite life for 150 targets (expecting 2 days of observation time per target with 50% efficiency). For bright to faint targets from ground-based transit surveys (NGTS), some of them requiring the observation of up to 10 transits, a total of 180 days of mission is foreseen (expecting an observing time of 12 hours per transit and 80% efficiency). Observations to detect the planets directly in reflected light will be possible for a handful of hot Jupiters and would require 75 days of mission (for a sample of 5 hot Jupiters). In total these programs combined require ~500 separate target pointings. Assuming 0.3 hours per pointing for acquisition and 10% margin on each program, the mission duration is estimated at ~950 days or 2.6 years. Adding to this duration the open time allocation (up to 20% of the observing time) and the commissioning phase of 0.2 years, the total required duration of the CHEOPS mission is estimated to be 3.5 years. An extended mission (5 years) would allow to significantly enhancing the science return of the mission. The rate of exoplanet discovery in the past years show that new exciting targets are likely to be discovered within the next 5 years. Furthermore, no other mission similar to CHEOPS is planned in this time frame (Plato will be launched in 2024), making CHEOPS a unique follow-up machine of wide astrophysical interest.

II. CHEOPS INSTRUMENT

A. Payload Description

The CHEOPS payload consists of only one instrument, a space telescope of 300mm clear aperture diameter, with a single focal plane.

The instrument assembly, also called CHEOPS Instrument System (CIS, fig. 1) is composed of four main units:

1) The Baffle and Cover Assembly (BCA) minimizes the stray-light and includes a protective cover and release mechanism.
2) The Optical Telescope Assembly (OTA) includes the structure carrying the telescope, the Back End Optics (BEO), the Focal Plane Module (FPM), and the radiators. In order to minimize the impact of thermo-elastic deformations on the instrument pointing, the optical heads of the platform star trackers will be mounted on the OTA, in proximity of the isostatic mounts of the instrument.
3) The Sensor Electronics Module (SEM)
4) The Back End Electronics (BEE)

CIS main specifications are given in the table below:

Table 1: CHEOPS Instrument System (CIS) main specifications.

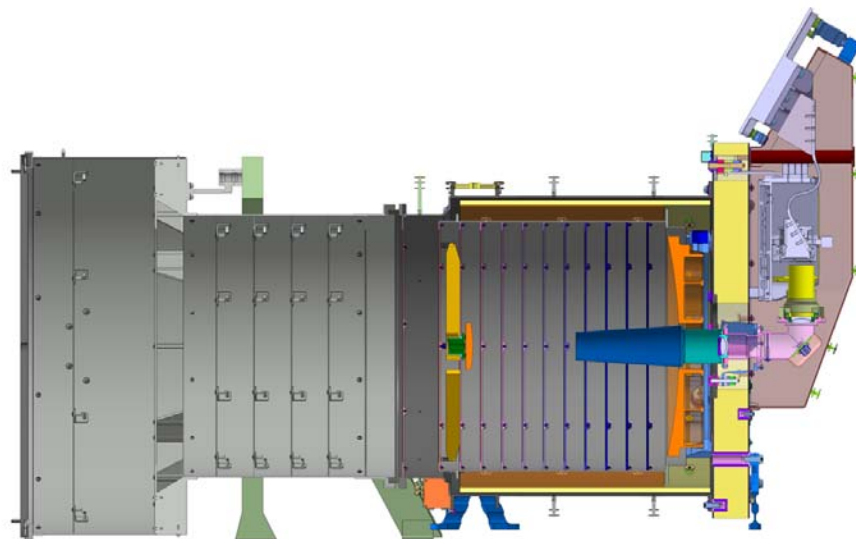| CHEOPS Instrument System	
Entrance pupil diameter	320mm
Central obstruction diameter	68mm
Working F/#	8.38 @ 750 nm
Effective focal length	2681 mm @ 750 nm
Telescope field of view diameter	0.32°
Spectral range	400 – 1100 nm
Pixel size	13 microns
Plate scale	1 arcsec/pixel
Detector focal plane	1024x1024 pixels
Detector Temperature	233K
Detector Stability	10mK
Instrument total Mass	<60kg including system margin
Instrument total nominal power	<60W orbit averaged including margin

Fig. 1: CHEOPS instrument

B. Telescope and Back-End Optics

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 the straylight rejection. The main design drivers are related to the compactness of the optical system and to the capability to reject the straylight. The entrance pupil is located at M1 and has a diameter of 320 mm. The central obstruction has a diameter of 68 mm (equal to the secondary mirror diameter) giving a relative central obstruction diameter of 0.2125. The effective collecting area is 76793 mm2 (about 8.64% more than the required one, i.e. an unobstructed telescope having an entrance pupil diameter 300 mm). This redundancy has been maintained to provide margin for possible lack of throughput efficiencies. In the baseline design, the

distance between M1 and M2 is 300 mm. The M1/M2 distance has been imposed as design constraint. This choice has been driven by the necessity to allow the accommodation of the satellite into the launcher. The telescope effective focal length is 1600 mm, giving a telescope focal ratio F/5. The focal plane has a diameter of 8.954 mm corresponding to a Field of View of 0.32degrees. At this location, a focal plane mask of the same size will be placed for the attenuation of the straylight background. A primary mirror internal baffle is foreseen for straylight rejection and radiation shielding purposes. The baffle shape is a truncated cone with the larger base having 60 mm diameter positioned at the M1 vertex, the height equal to 150 mm and parallel to the telescope optical axis and the smaller base with diameter of 39 mm. Introducing such baffle will diminish the straylight background of about 20% and will increase the shielding of the BEO lenses from potentially damaging incoming radiation.
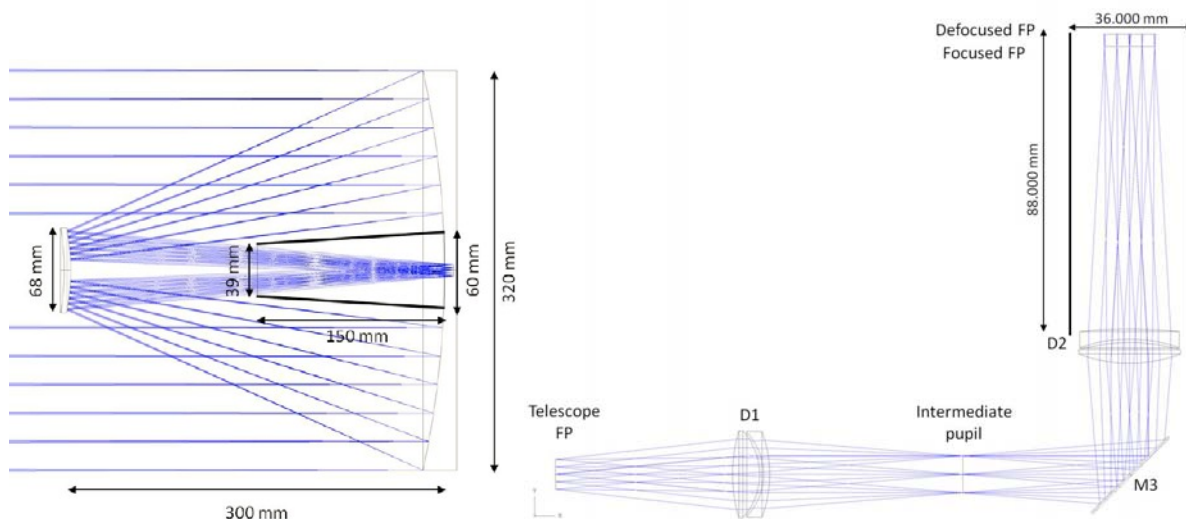

Fig. 2. CHEOPS optical design (INAF): Telescope (left) and Back-End-Optics (right)

The BEO is basically composed by three elements: a collimator (D1) which forms an intermediate pupil, a flat fold mirror (M3) which is inserted to minimize the envelope of the whole optical system and a camera (D2) that reimages the focal plane at the required plate scale. The BEO has been optimized on a Field of View with diameters 0.32 degrees. The detector area of interest, corresponding to the window centered to the pointed object, is 200×200 pixels and its location will set inside the optimized Field of View. The design of the collimator and the camera is based on two spaced achromatic doublets.

The CIS optical design is intended to produce a relatively wide point spread function at the detector plane. The width of the PSF is a trade-off between reducing the noise in the stellar image (pushing to large PSFs) and the increased susceptibility to straylight which a larger stellar image generates.

The theoretical PSF shape is a top-hat cylinder having diameter of about 30 arcsec (i.e., 30 pixels). A figure of merit to evaluate the performance has been derived by considering the optical PSFs, the jitter effect and the flat field performances. The result of the simulations has pointed out that a defocused PSF gives sufficient performance to meet the requirements (see Fig. 3, [5]). PSFs have been generated at the defocused focal plane (about 3.5 mm from the nominal focal plane) with a flat spectral wavelength between 400 and 1100 nm with a spectral sampling of 50 nm. They have been spatially sampled with a subpixel size of 1.3 micron corresponding to $1/10^{th}$ of the nominal detector pixel

Fig. 3. CHEOPS defocused PSF. The color gradient indicates the relative energy distribution. The axis x, y correspond to the (10x oversampled) pixels in the detector (INAF).

size. Moving from the center of the field of view to the edge, anisotropy starts to affect PSFs while at the very edge the PSF starts to be dominated by aberrations. As expected, in the PSF the feature due to the telescope central obstruction and to the Poisson spot can be clearly seen.
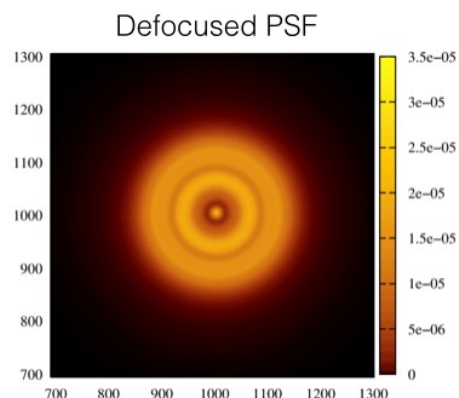
B. Baffle and Cover Assembly (BCA)

The Baffle and Cover assembly (BCA) is the key to the stray light mitigation strategy of the CHEOPS instrument. The external baffle goal is to limit the amount of straylight issued from sources located more than 35° from the optical axis. The baffle design as well as the cover and actuator are of *CoRoT* heritage. The purpose of the cover is to provide a light tight lid as well as contamination control for the telescope integration prior to launch. The cover release mechanism is based on a spring-loaded hinge and a launch lock mechanism. The launch lock is based on a Frangibolt actuator design. This solution provides reliability and also avoids contamination issues during launch and early orbital phase.

C. *Focal Plane Module (FPM) and Sensor Electronics Module (SEM)*

The detector selected is an e2v CCD47-20 (13-μm pixel 1k × 1k , AIMO). The CCD will be nominally operated at 233K. The flight model (FM) CCD will be characterized prior to installation in the proto flight model (PFM) instrument.

There are two electrical modules for interfacing, controlling and reading-out the CCD detector, the FPM located on the optical bench and the SEM located inside the platform. The FPM (Focal Plane Module) contains the FPA (Focal Plane Assembly) where the CCD is located and the FEE (Front End Electronics) both with two separate interfaces to the radiator for cooling down the units. The SEM as a physically separated module and electrical harness to the FPM/FEE contains a SCU (Sensor Control Unit) and a PCU (Power Conditioning Unit) interfacing the DPU (Data Processing Unit) and the PSU (Power Supply Unit). Both, the DPU and PSU are integrated in the BEE (Back End Electronics) located inside the platform. Electrical sub-systems architecture is given fig. 4.

The FPM-SEM architecture is mainly driven by the thermal design having 3 different categories reflecting the requirements of thermal control.
1. Focal Plane Assembly (FPA) with CCD and proximity electronics operating at lower than 233K nominally stabilized by heating against a dedicated radiator
2. Front End Electronics (FEE) with analog and CCD low level control electronics operating between 253 – 283 K stabilized by heating against a dedicated radiator
3. Sensor Controller Unit and Power Conditioning Unit (SCU & PCU), including FPGA – based digital electronics for data handling and controlling the CCD detector by different readout modes at standard temperatures without stabilization needs.

Due to the sensitivity of signals and clocks against cross talk and disturbances the analogue electronics according 1 and 2 is organized in close vicinity.

The gain stability of the analog electronics over several hours is one of the most important design drivers for selecting the EEE components and designing the electronics in detail. Especially the BIAS and clock voltages have to be very stable because of the significant sensitivity of the CCD against voltage drifts. The challenge is to use available space qualified components which fulfil required thermal drift characteristics of gain and offset parameters but have adequate electrical performance fulfilling the low read-out and quantization noise requirements. Even if a temperature stabilization of dedicated electronics areas is foreseen a favored very low stability (or very low systematic error) of 10ppm over hours requires extended calibration of the electronics e.g. measurement the CCD BIAS voltage drift vs temperature.

The current design philosophy is to maximize fault tolerance of the digital and analogue subsystems by avoiding single points of failure (SPF). This has led to a cold redundant design for SEM and BEE. The FPM also is cold redundant to a large degree, with the exception of the CCD, the CCD clock driver and BIAS voltage supply.

The channel is selected by powering-on either the main or redundant electronics chain. The SEM main/redundant channels and BEE main/redundant channels are powered separately, so that an operation of main/main or redundant/redundant is possible if one chain fails. A cross-strapping at the SpaceWire links and secondary power voltages are not foreseen. The data are acquired by the BEE/DPU either from the main or redundant SpaceWire link.
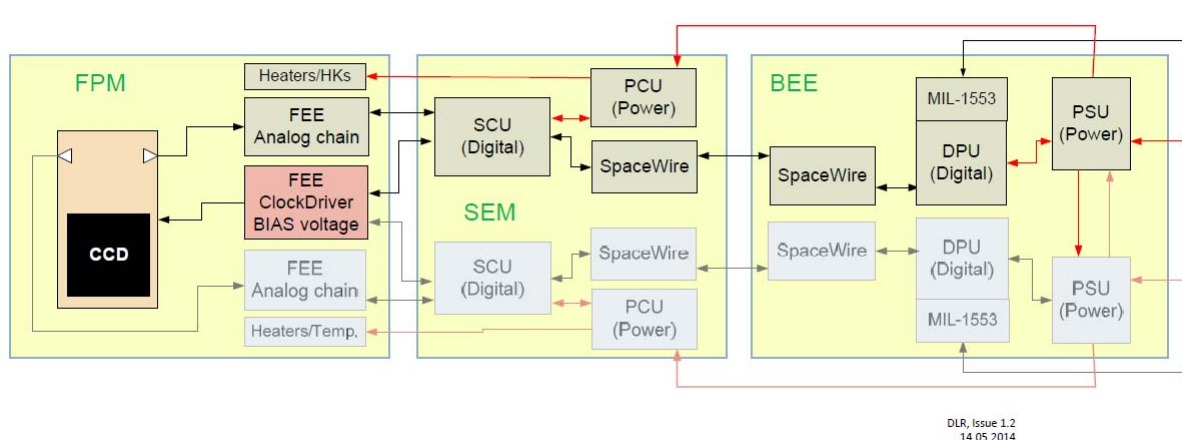
Fig. 4. CHEOPS Electrical sub-system fault tolerance architecture (DLR)

D. Back End Electronics (BEE)

The BEE is composed of the DPU (Data Processing Unit) and the PSU (Power Supply Unit). The main task of the DPU besides the communication with the camera read-out electronics is the compression and packaging of telemetry data. The DPU will also compute centroid the stellar images and transmit it to the spacecraft AOCS thereby allowing more accurate control of the spacecraft pointing (requirement of <8").

The RPW DPU hardware is based on the GR712, which contains two LEON3 processors and provides space wire and MIL-1553 interfaces. The DPU carries a mass memory to allow for 3 days operation without ground contact. 3D-Plus provides a FLASH memory in the configuration of 4 Gbit times eight bit. For effective operation of the processor four components are used to provide 32bit access and EDAC. The present configuration foresees the flash memory for storage of telemetry data. In addition the onboard back-up of the application software shall be stored in this area. To increase the reliability, in particular for the back-up of the application software, it is recommended to keep more than one copies, located at different pages. Four standard chips are combined to a stack and packed into a common package. The total height of the stack is ap-prox. 12 mm. Due to this configuration it is unlikely that one high energetic particle would hit a similar address range on all pages at the same time. The four chips are accessed by individual chip enable, read and write enable signals. The command latch enable and the address latch enable is common for all four chips. The total size of the memory to be used for data will be 32 bit times 4 GBit (128 Gbit = 16 GByte). It is recommended to organize the mass memory as a ring-buffer. This would use all memory cells with the same fre-quency. In this case approximately ~127 Gbit are available. Since the average telemetry is 1.2 Gbit/day, the same memory cell will be used approx. three times per year. Therefore the limited life time of the component (~100.000 write cycles) is negligible.

The PSU provides dedicated DC-DC converters for the DPU and the SEM & FPM with high accurate secondary voltages and switches to control up to four instrument operational heaters. The S/C interface includes an EMC filter, solid state switches for ON/OFF control and the status monitoring. Presently it is foreseen to have temperature sensor connected to the analogue telemetry provided by the S/C.

III. CONCLUSION

As the first small mission (S-mission) in ESA's Science Programme, CHEOPS is truly a pathfinder. The tight schedule of small missions are extremely challenging. After successful Instrument PDR in July 2014, manufacturing of STM for all sub-systems will start before the end of 2014 in order to allow CIS STM integration to the platform end of March 2015. CIS PFM delivery to the platform is expected end of December 2016 for a launch readiness in December 2017.

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