The CoRoT Legacy Book

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V.2

CoRoT heritage in future missions

M. Ollivier[1, 2], D. Tiphène[2], R. Samadi[2], and P. Levacher[3]

[1] Institut d'Astrophysique Spatiale, UMR8617, CNRS, Université Paris XI, Bâtiment 121, 91405, Orsay Cedex, France
[2] LESIA – Observatoire de PARIS
[3] Laboratoire d'Astrophysique de Marseille

1. CoRoT heritage: The CHEOPS mission (by M. Ollivier)

Among the space missions dedicated to accurate stellar photometry, CHEOPS (ESA-2013, Fig. V.2.1) is certainly the mission that benefits the most from the CoRoT developments.

CHEOPS is the first mission of the ESA S programme (small missions, with a fast development concept and an ESA contribution limited to 50 M€). It is dedicated to the accurate photometry of stars with known planets (from Jupiter size to super Earths) identified by radial velocimetry in order to determine, when planets transit, their radius with an accuracy of 10% and their global density with an accuracy of about 30%. CHEOPS aims also at providing first order characterisation of transiting planets with an atmosphere that will be studied by next generation of spectro-photometers.

In order to reduce the development time and associated costs, CHEOPS uses subsystems and developments made in the context of CoRoT:

- the orbit and the altitude at which CHEOPS will observe benefit from CoRoT ones (polar orbit). As a consequence, the space environment seen by the satellite will be known before the lauch, and particularly the amount of proton impacts due to South Atlantic anomaly crossing;
- the CCD is a 1k × 1k E2V component based on the same technology as the CCDs used by CoRoT. As a consequence, all the calibrations done on CoRoT CCDs can be reproduced identically. In the same time, the ageing of the detector can be anticipated, with, for example, an increase with time of the dark current, of the coefficient of transfer inefficiency, of bad pixels due to protons impacts, etc.;
- the thermal control of the CCD is based on the same principle. The focal plane is linked to a radiator at about −40 °C, and the working temperature of the focal array is stabilised at a slightly higher temperature thanks to a servo-control thermal heater;
- the attitude in orbit control system (AOCS), where the instrument is used to determine accurately the direction of the line of sight thanks to the measurement of the photocentre of stars in the field, is directly derived from the CoRoT AOCS principle. In the case of CoRoT, 2 bright stars in the bright stars channel, used also for the science programme, were monitored to provide an error signal to the control system of the satellite;
- the optical baffle, in front of the telescope, used to drastically reduce the amount of the scattered light (off axis-light) is developed by the same company as CoRoT. The requirements and the concept of the baffle are the same, using the same materials, the same shape for the vans, and probably the same black coating;
- the device used to open the telescope protective cover is the same as CoRoT. It is a one-shot device that allows a soft but complete opening of the cover without introducing parasitic moves;
- the surface of CHEOPS PSF is comparable to the size of the faint stars channel CoRoT PSF, i.e.: about 500 square arcsec. As a consequence, the level of contamination by faint background stars will be the

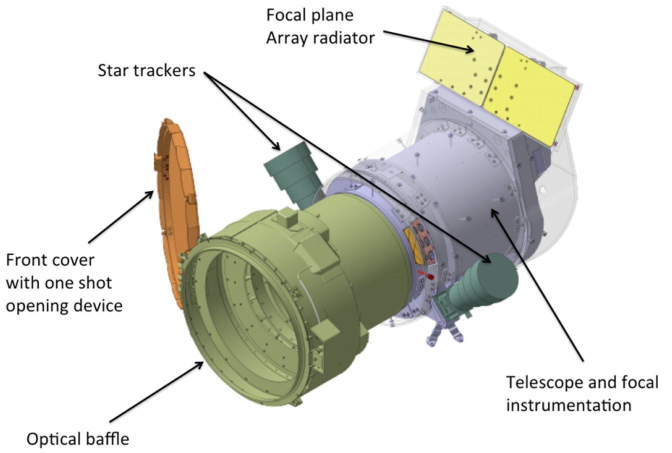

Fig. V.2.1. The CHEOPS photometer. Adopting the concept developed for CoRoT, the CHEOPS photometer is made of a telescope with a focal plane array which is passively cooled down by means of a radiator, the temperature being controlled by a servo-system slightly heating the detector at the reference temperature. The scattered light is strongly reduced by the use of an optical baffle in front of the telescope. The telescope is pointed by using star trackers, the fine-tuning being controlled by the instrument itself (© Bern University).

same (assuming a similar stellar density). The contamination study strategy can thus be adapted from the CoRoT strategy;
– last but not least, the ground segment and in particular, the reduction pipeline is strongly inspired by the CoRoT pipelines. Even if CHEOPS is downloading 200 × 200 pixels imagettes, the photometric light curves extracted from the images are obtained more or less in the same way as CoRoT light curves imagettes. Of course, the CHEOPS pipeline has to take into account the specificity of the observations (rotating field, defocused tri-foiled PSF, etc.)

For more information see CHEOPS: CHaracterising ExOPlanet Satellite, Definition study report, 2013, ESA/SRE, 7, available on ESA website

2. CoRoT heritage: The PLATO mission (by D. Tiphène, R. Samadi, P. Levacher)

The PLATO mission belongs to the M-class missions of the ESA Cosmic Vision 2015–2025 program.

PLATO re-uses the concept of high accuracy photometry used by CoRoT mission.

What characterises PLATO at first look is the high number of cameras instead of a single photometer in most general cases. It comes directly from the need of an instrument with a large entrance pupil to fulfil the needed signal-to-noise ratio, but with a pupil divided by several cameras to have both a high number of bright stars without saturation and reach a high signal-to-noise ratio. That comes, as for CoRoT, by the need to confirm by ground observations the events detected on-board, to check if they are effectively exoplanets or other detections, and these accurate observations (with large Earth telescopes) are only possible for bright stars (magnitudes up to about 11). Unlike COROT, PLATO will allow a seismic study of the host stars brighter than magnitude 11. This will enable the precise characterisation of the planet host star, including its age and mass.

Taking into account the constraints of CoRoT, in particular for stray light reduction, and therefore the very large optical baffle behind the instrument, PLATO has completely changed the approach by selecting an orbit far from the Earth: Lagrange point L2 of the Sun-Earth system. Such an orbit also authorises the use of the immense field of view we have mentioned, and long observation periods up to 3 years on the same part of the sky, with limited constraints on the satellite attitudes. The PLATO thermal concept also takes advantage of the selected orbit avoiding large thermal variable fluxes on the instrument; CoRoT's orbit was a 895 km polar orbit with large thermal variations on the outer of the instrument due to the proximity of the Earth. The thermal of a photometer should be optimised to guaranty a very stable environment to the temperature-sensitive equipments (detectors, optics. . .).

The main driver for choosing the PLATO instrument basic configuration is related to the need to optimise simultaneously the number and the brightness of observed cool dwarfs and subgiants. The concept of overlapping field-of-view, offering a very wide field of view covered by a variable number of cameras, was a natural consequence of this main idea. In addition to this basic motivation, the overlapping field-of-view allows to re-observe, during the PLATO step-and-stare phase, some stars for which particularly interesting planets were detected in the long monitoring phases of the mission (in particular telluric planets in the habitable zone), but only with a subset of telescopes, therefore without reaching the required photometric precision for seismic analysis during these phases. During the step-and-stare phase, these targets can be put in the part of the field observed with all the 32 telescopes, thus reaching the best photometric precision, giving us the potential to fulfil photometric requirements.

The detector saturation level is linked to the pupil size, optical transmission, exposure time, full well capacity (FWC), PSF size and shape, quantum efficiency of the charge-coupled device (CCD), and star brightness. The FWC of CoRoT CCDs was reduced by the choice of advanced inverted mode operation to limit the surface dark current at −40 °C. With the pupil size selected and the PSF size largely constrained by confusion issues, a special effort was made on the PLATO CCDs for a large increase of the FWC, in order to improve the access to bright stars, which are of major interest for science. Moreover, the preparation of CoRoT has shown the possibility to exploit photometrically slightly saturated spots, an option which Kepler is using extensively as well. For PLATO, this possibility will also be used to increase the useful magnitude range; the dimensioning of signal chains is such that saturation occurs for normal cameras between 8.3 and 9.5 depending on the position of the star in the field of view, further assuming that PLATO bright stars photometry could be studied by four magnitudes on saturated images. Moreover, the performances of cameras are strongly linked to its temperature stability. Cameras shall be strongly isolated from temperature variable (or not controlled) sources (sunshield inner surfaces, optical bench...). As for CoRoT, the power dissipated inside the FPA is fixed on timescales higher than the cycle time.

PLATO has the double particularity to be a very high accurate relative photometer and to have a science bandwidth at very low frequencies. The periodic perturbations in the seismic observation range (100 sec–4 days) shall be reduced as much as possible. The resulting need is a very low instrumental noise in the science frequency bandwidth, in terms of random noise or parasitic lines, fixed or slightly moving in the Fourier spectrum; this constraint was already a strong scientist CoRoT requirement. For this last need in particular, the resulting constraint is to limit the number of various oscillators, each with its own frequency to avoid or limit the risk of beating between these oscillators. All the activities of the cameras are synchronised by a unique reference clock distributed to all sensitive boxes. Indeed, the level of noise required at instrument level is very low, an EMC coupling between electronics boxes or between cables at such low levels is inevitable and could not be seen during EMC tests, due to a low detector sensitivity at room temperature. This could be a high risk of damage in the performances for the two scientific programs. Then, the general philosophy for the PLATO photometers is to synchronise all the activities especially on low level analog electronics (detectors, attached video electronics and their power supplies), and in their close environment (camera with active thermal control). With this precaution, an eventual EMC coupling between two or several subsystems will only result on a fixed pattern in the data, which can be managed like other stable perturbations.

Early in the CoRoT mission analysis, the perturbations and sources of noise having an important impact on the quality of the data have been identified:

- after each integration phase, CCD pixels are read out while they remain sensitive to the incident light (no shutter) and produce the "smearing" effect. Each star image has a uniformly bright "tail" along columns. The magnitude of this offset depends on the ratio of the readout time to the integration time. CoRoT has shown that this offset could be measured and subtracted;
- variations of the satellite pointing direction induce short-term displacements of the stars, called jitter. Hence, due to the fixed position of the photometric mask, small part of the star flux can be detected by pixels outside the mask, and then not sum in the photometrical signal. Additionally, part of the flux from a neighbouring parasite can enter the mask and pollute the photometry of the target. In either case, the flux of the target will be modulated by the coherent and incoherent variations of the pointing direction of the satellite;
- PLATO should be more sensitive to confusion than CoRoT: stars fainter than around magnitude 11 are expected to be perturbed by fainter stars (contaminants). Three different types of perturbations are identified: photon noise from the contaminants, combined effect of confusion and satellite jitter, and the flux of the contaminant introducing a bias on the measurement of the depth of transit and for seismic analysis;
- deriving for each star the associated sky background flux is of major importance, not only for the analysis of the transit depth or the seismic analysis, but also for the photometry measurements based on weighted mask and for the photometric jitter correction. Indeed, an incorrect value for the background level decreases the efficiency of the weighted mask with respect to the confusion problem as well as the efficiency of the photometric jitter correction;
- the kinematic differential aberration is due to the relativistic effect related to the satellite motion with respect to the stars; the angle between two stars varies with time. This effect is true for all missions and will be more important for PLATO due to the large field of view;
- for PLATO, the instrument response functions will be more complex than the CoRoT ones. The star light curves will be different for each camera due to the different gain of each electronic chain, the different quantum efficiency of each CDD, and the differing aperture and transparency of each telescope. Furthermore, crosstalk between different electronic chains are expected to occur and will introduce an absolute offset on the photometry measurements. Although this bias will be constant, it will nevertheless be different from one camera to another. Therefore, before comparing and averaging (temporally and spatially) the light curves associated with the same star but coming from different telescopes, it will be necessary to transform the digital signal into a signal that can be directly compared and averaged. This is why a correction of the global gain of the instrument (optical, CDD and electronic) as well the crosstalk patterns must be performed prior any comparison and averaging of the light curves. CoRoT has measured the varying of the global gain of electronics chains with the temperature;
- the occurrence of a cosmic ray or a glitch can perturb a light curve. Such outliers introduce important artefacts, in particular on the Fourier analysis. Hence, impacted measurements must be removed and replaced by a representative value of the star flux;
- long-term trend has been measured by CoRoT; a long-term decrease of the intensity at long-time scale (from weeks to several months) has appeared due to the aging of the optics and of the CCD, and has been corrected afterward on-ground; similar correction will be applied on the individual PLATO light curves;
- thermo-elastic differential variations of the PLATO telescope structures will induce a variation of the line of sight of a given telescope with respect to the pointing direction of the fast telescope used as reference for the pointing. These variations will in turn induce additional and undesirable displacements of the stars, which have the same impact on the photometry as the kinematic differential aberration mentioned above, whereas these effects did not exist in CoRoT photometer, which had only one telescope.

The data processing chain (board and ground) of the space mission PLATO is currently being defined. During the assessment study phase (2008–2009) as well as the phase A (2010–2011), a preliminary definition of the data processing chain has been proposed. This work benefited greatly from the experience gained on CoRoT. This is not surprising. Both missions have similar requirements and characteristics. Indeed, like CoRoT, PLATO requires a very high photometry precision (34 ppm per hour at $V = 11$ for PLATO, 8 ppm per hour at $V = 6$ for CoRoT) and a very long-term stability of the measurements (several months). Furthermore, like for CoRoT, in order to archive the scientific requirements of the PLATO mission is it necessary to correct the raw data from undesirable disturbances, such as the satellite jitter described above.

Several methods for correcting the noise induced by the jitter have been investigated by the CoRoT data processing algorithm team (called GT2S[1]). It turned out that the most efficient were the ones developed by De Oliveira Fialho et al.[2]. This method requires knowing the point-spread function (PSF) of the camera with a spatial resolution significantly smaller than the pixel size and at different positions of the field of view. It is also required to know the angular displacements of each target. Once these information are available, we can then predict and correct the relative variation of the flux induced by the satellite jitter. This "jitter correction" will be implemented in the PLATO on-ground data processing chain and operated on the raw PLATO light curves.

Building a super-resolved PSF from pixel-resolved ones is possible, in practice, through the exploitation of subpixel motion. Before starting an observation sequence, several

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[1] GT2S: Groupe Traitement Segment Sol.

[2] Jitter Correction Algorithms for the COROT Satellite – De Oliveira et al. 2007, PASP, 119, 337).

different calibration processes need to be applied. A time-series of small imagettes are then acquired during the motion of the satellite. These imagettes are downloaded and then inverted (on-ground) to produce the PSFs at the target location. While CoRoT used times-series of small imagettes acquired during a few days at the beginning of each observation sequence[3], PLATO will rely on a microscanning technique that will be operated during the calibration phases of the missions. In this approach, the instrument's attitude control system is used to execute a slow, controlled perturbation of the line of sight of the telescope in such a way that the image of a star on the CCD will move over the area of about a square pixel.

Zodiacal stray light is expected to be the major contributor to the background for PLATO; in the case of CoRoT, the stray light was mostly due to Earth. This source is expected to vary on the long term (approximately one month). Since the momentum wheels will be unloaded approximately each week, we will use this as an opportunity to recalibrate the background map. In terms of spatial distribution, the Zodiacal stray light is also expected to vary at large scale-length. Accordingly, we can expect that such variation can be modelled using a functional form (e.g. a bivariate polynomial). The parameters of this functional form will be fitted during the configuration mode using several measurements of the background performed at different locations of a full image. Once the free parameters are adjusted, they will be used during the observation mode to derive the background associated with each target.

The overall architecture of the pipeline is directly inherited from the CoRoT mission, and allows anticipating known perturbations. Some of the specific corrections used for PLATO are identical to the ones used for CoRoT, such as the jitter correction, and some others are strongly inspired by the work done during the CoRoT mission.

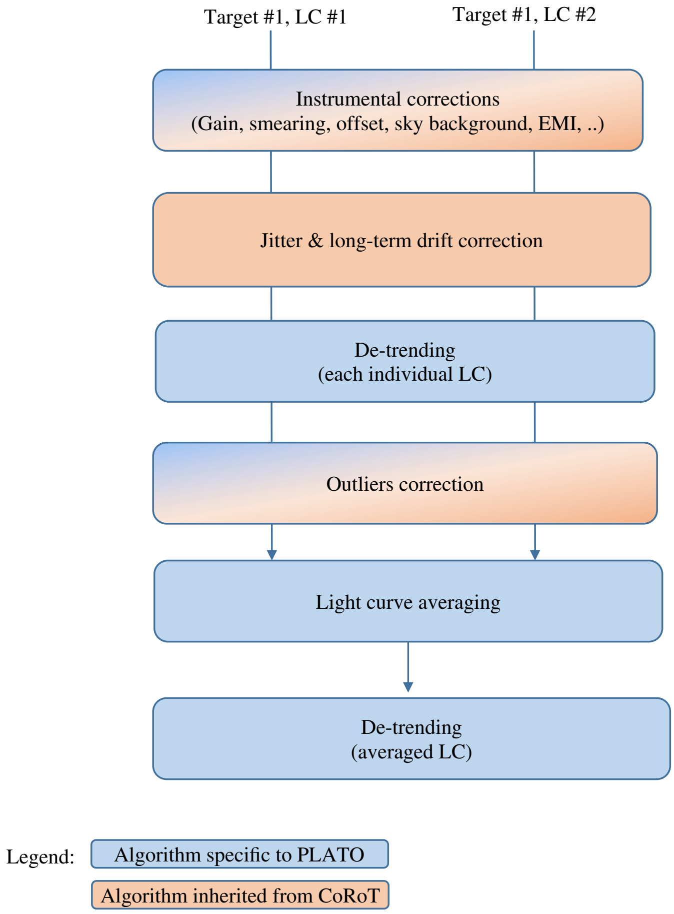

Fig. V.2.2. Preliminary design of the on-ground processing pipeline for the PLATO mission. © Emmanuel Grolleau, LESIA

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[3] Radiation effects on space-based stellar photometry: theoretical models and empirical results for CoRoT Space Telescope – Pinheiro da Silva et al. 2008, MNRAS, 384, 1337.