PLATO

Executive Summary

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1. INTRODUCTION

PLATO (PLAnetary Transits and Oscillations of stars) is one of the six candidate medium-class (M) scientific missions of the ESA Cosmic Vision (CV) program. If selected, it will undergo a Definition Phase and then an Implementation Phase for launch in 2017-2018.

Two parallel 1-year assessment studies have been just concluded. One of these studies was led by Thales Alenia Space Italia (responsible of the system definition and the platform design) with Thales Alenia Space France (responsible of the payload).

Scope of the assessment study was to provide technical definition and programmatic assessments of the whole space segment (spacecraft + payload), including development schedule and industrial costs evaluation. These pieces of information will support the selection process of the M mission to enter the Definition Phase in the first half of 2010.

2. PLATO MISSION

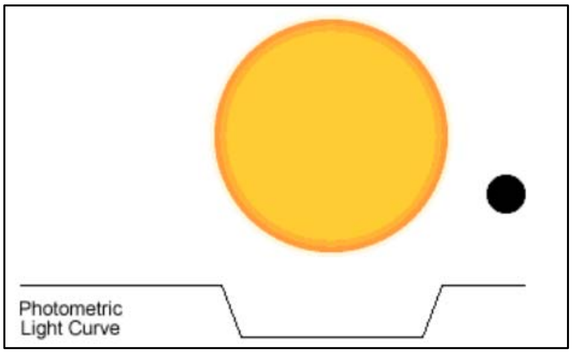
2.1 Scientific Objectives

The primary objective of PLATO is to discover and study extrasolar planetary systems. The second important objective is to perform seismic analysis for a very large sample of stars.

Thanks to its innovative multi-camera instrument and to very long duration observations, PLATO will extend the knowledge of exoplanetary systems and their host stars initiated with CoRoT and followed up by Kepler, by surveying many more stars with sensitivity improved by at least an order of magnitude, allowing detection of Earth-sized planets.

2.2 Measurement Concept

Extrasolar planets will be discovered by PLATO by means of very accurate photometric measurements of the light curve of the stars over a long time period (14 hrs): the transit of a planet in front of the host star produces attenuation in the light curve. From the photometric measurements, the physical characteristics of detected planets and of the host stars (mass, orbit, age, chemical composition) will be also determined, and the star oscillation models will be characterized (asteroseismology).



2.3 Mission Requirements

PLATO will be launched by Soyuz-Fregat from Kourou into transfer trajectory to a large libration orbit around the earth-sun Lagrange point L2. During an operational lifetime of 6 to 7 years, the operation plan includes 2 long stare observations (2-3 years each) of different sky zones on opposite hemispheres, plus 1-2 years step-and-stare observations. During the observations, the satellite will be inertially pointed, with the constraint of keeping a solar aspect angle (SAA) of $\pm 15°$ from the solar panel/sun shield axis. For this reason, a 30° reorientation manoeuvre is planned every 30 days.

For each of the 2 year-long stare observation fields, it is required to observe 5 star samples, plus an additional one as a goal (Table 2-1).

Sample 1 =	**10000 cool dwarfs per FOV, 27 ppm/hour noise**
Sample 2 =	**40000 cool dwarfs per FOV, 80 ppm/hour noise**
Sample 2 =	**40000 cool dwarfs per FOV, 27 ppm/hour noise (design goal)**
Sample 3 =	**500 cool dwarfs per FOV, 27 ppm/hour noise**
Sample 4 =	**1500 cool dwarfs per FOV, 27 ppm/hour noise**
Sample 5 =	**125000 cool dwarfs per FOV, 80 ppm/hour noise**

Table 2-1 : Star sample requirements

The non-photonic noise must be ≤ 1/3 of the photonic noise, and the encircled energy of the observation window must be ≥ 90% in a 2x2 pixel mask. Colour information on target stars is required.

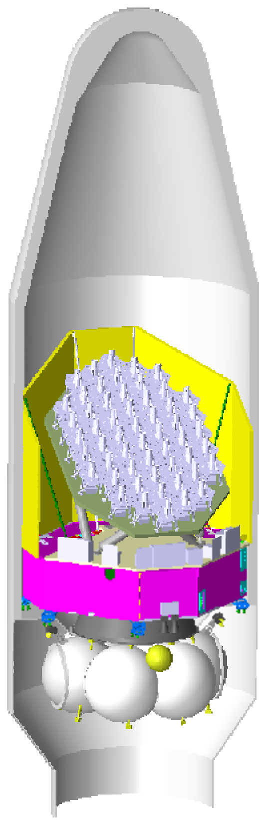
Fulfilling the above requirements implies the maximization of the following design parameters:

- telescope Field of view (FOV) → driver for the optical design;
- total collecting area → driver for the selection of the number of telescopes; impacts on mass, power consumption, instrument overall envelope;
- platform pointing stability → driver for AOCS sizing and thermo-mechanical design.

3. SATELLITE DESIGN

3.1 Satellite Configuration

PLATO was designed around an innovative “54 staring cameras” payload concept, inspired by the multi-collectors design developed in the Eddington study. The FOV of each telescope is 625 deg^2. The overall light collecting area is ~0.3 m^2.



The payload is installed on a platform conceptually derived from the service module (SVM) of Herschel. The platform supports a sunshield, which is sized to protect the payload within a solar aspect angle = ±15° (Z) and ±30°(Y). The solar arrays are body-mounted on three sides of the sunshield and SVM.

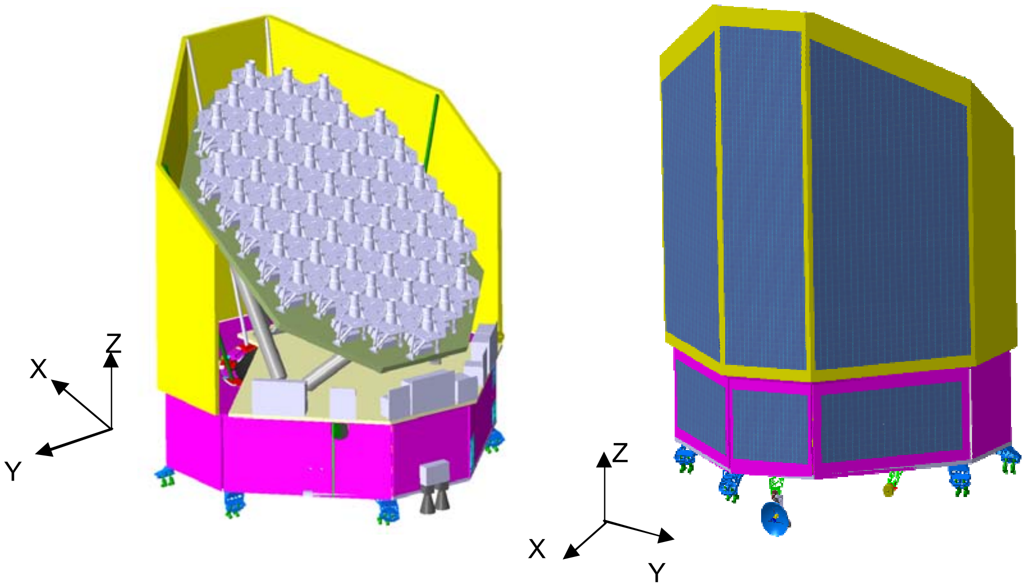


Figure 3-1 : Satellite configuration on-orbit and under the Soyuz fairing

The satellite baseline design was identified by means of design trade-offs performed at system, SVM and PLM level.

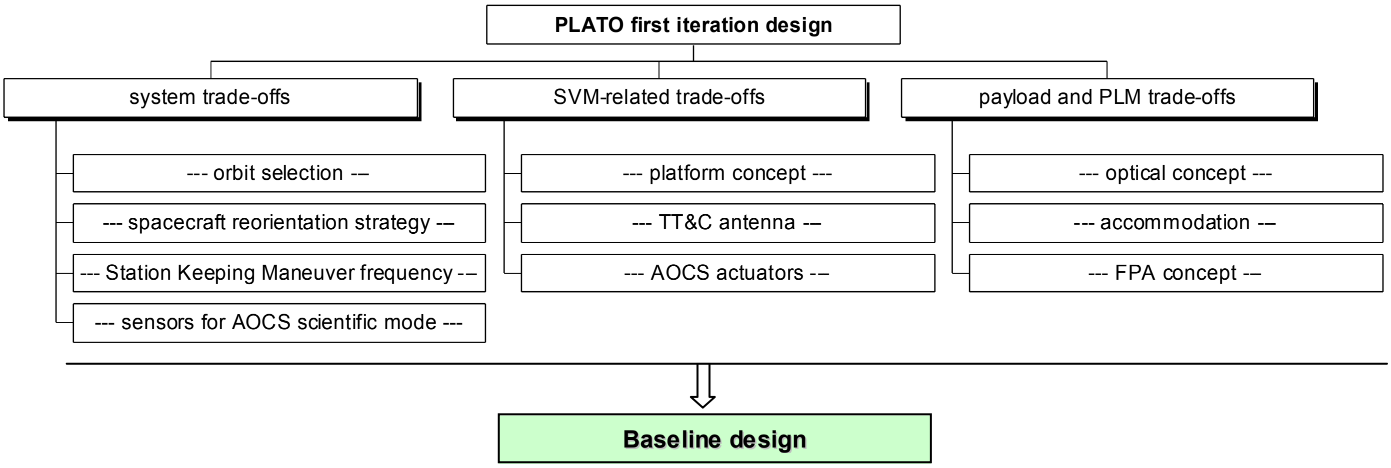
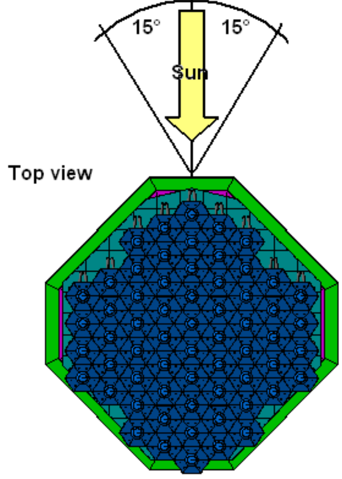


Figure 3-2 : trade-off tree

3.2 System-Level Trade-offs

Orbit selection (**large- vs. narrow-amplitude orbit**). A narrow-amplitude (Lissajous) orbit around L2 is subjected to less straylight due to Earth /Moon shine. However, it is heavily penalized in mass due to the higher amount of propellant required, and can be subjected to periodic eclipse. A Large libration orbit is selected, eclipse-free and requiring the minimum quantity of propellant.



Satellite reorientation (**30°** vs. **90°** vs. **180°** periodic stepwise rotations). PLATO must be periodically turned around its Z axis to maintain the telescope array always in the shadow of the sunshield and the solar panels sufficiently illuminated. These manoeuvres disturb the staring observation and must as infrequent as possible. However, the longer is the time interval, the larger the reorientation angle, with impacts on the sunshield and solar array size and the thermoelastic strains. A baseline with sun-reorientation steps of 30° every 30 days is chosen as best compromise, requiring a reasonable sunshield size and mass; furthermore it simplifies the solar array design, still allowing the use of body mounted panels, while larger reorientation angles would require steerable wing panels to compensate the large SAA variation.

Station keeping manoeuvre frequency (**30** vs. **92 days**). Orbit maintenance manoeuvres are needed to counteract the instability. Frequent manoeuvres penalize the instrument duty cycle, while too long time intervals cause the attitude errors to diverge, so as to require a lot of propellant to be corrected. A baseline strategy of station keeping manoeuvres every 30 days fits the propellant budget with the instrument duty cycle.

Attitude fine measurement (**star trackers** vs. **payload telescopes**). On-board attitude measurement is generally performed by means of gyroscopes + star trackers. Involving the payload in attitude determination can improve the performance at the cost of more complication due to the management of payload data in the AOCS loop. The PLATO pointing stability requirement during science observation is severe and covers frequencies in the range 0.02÷40 mHz (<0.5 ”/√Hz) and higher than 0.04 Hz (<0.5”). For trade-off purpose a preliminary allocation between thermo-mechanical stability and AOCS attitude control error has been obtained. From this it results evident that the requirement for attitude control error (Relative Pointing Error, RPE) in the range 0.02÷40 mHz (<0.2"/√Hz) is not compatible with the use of gyroscopes + star-trackers. The baseline architecture foresees, for on-board attitude determination, to use off-the-shelf gyroscopes + payload data.

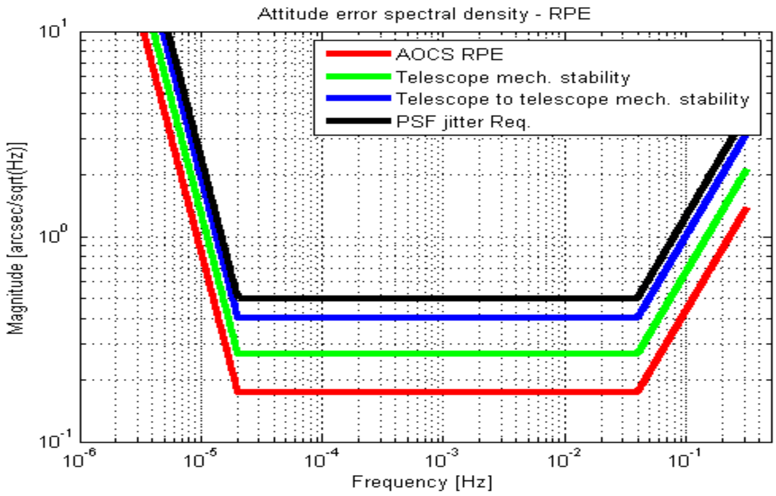


Figure 3-3 : PSF jitter requirement – Preliminary allocation

3.3 Payload-level Trade-offs

The first part of the study was dedicated to the trade-off between candidate architectures able to fulfil both science requirements and system and programmatic constraints. Different aspects have been put in the balance:

- Science return, which drives collecting area (at least 0.3 m²), instantaneous field-of-view (size and shape), and instrument performance (image quality, noise level);
- System constraints: mass, volume, power and interfaces;
- Number of detectors and telescopes that can be procured and assembled within the PLATO implementation timeframe;
- Number of CCDs per telescope, leading to focal planes able to fulfil simultaneously field-of-view, image quality and angular resolution requirements while considering CCDs manufacturable with state-of-the-art technology. Up to four CCDs per focal plane.

Considering the field-of-view required, reflective and refractive solutions are possible with acceptable f-number (around 3 or above). The following families were identified[1] :

- The so-called fully refractive "dioptric solution", using only lenses ;
- The so-called fully reflective "catoptric solution", using mirrors (Three-Mirror Anastigmat) ;
- A mix called "catadioptric solution" : lenses are added to mirrors ;
- And a One-Mirror-Anastigmat, in which light is reflected by one mirror towards lenses.

A wide range of degrees of freedom were open (number and size of collectors, focal plane geometry). Combining them with the optical concepts led to a large number of options. Among them, no less than 16 were possible candidates for PLATO. We have analyzed them thoroughly, from the opto-mechanical design to the accommodation on the satellite and under the launcher fairing.

Then we have traded-off the solutions, obeying to the following rationale:

- Candidate configurations have been readied with their best possible accommodation ;
- Selection criteria and weights have been derived ;
- Marks have been given to each candidate configuration ;
- Candidate configurations have been ranked.

At the end of the exercise, two lands of solutions were emerging, both based on a dioptric optical concept which accommodability leads to the most science-effective solutions :

[1] When using only lenses (dioptric solution), collectors will be called "cameras", whereas they will be called "telescopes" when one or more mirrors are used

- Of the order of 30 cameras, with the advantage of requiring less power ;
- Of the order of 60 cameras, with the advantage of having smaller lenses.

After a last step of fine tuning and further design optimisation, in particular in the fields of electrical architecture and optical design, we converged towards what we claim being the best compromise for PLATO : 54 staring cameras with a pupil diameter of 83 mm. This reference design was selected for consolidation during the remaining time of the Study ("Design Phase" and "Programmatics Phase").

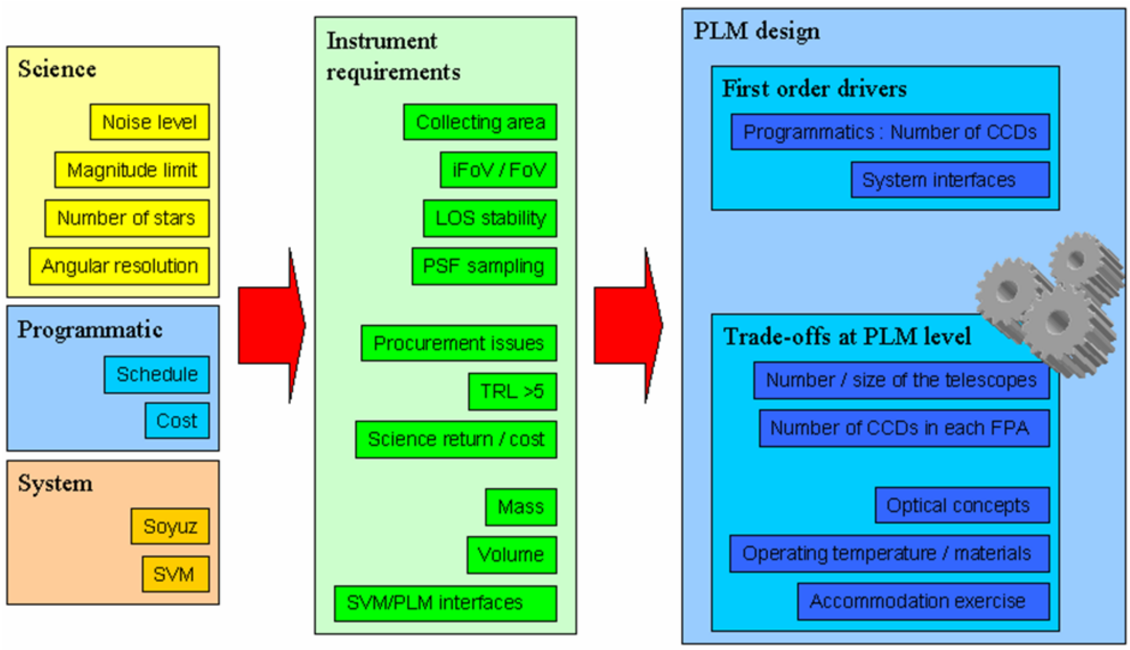


Figure 3-4 : Payload-level trade-off logic.

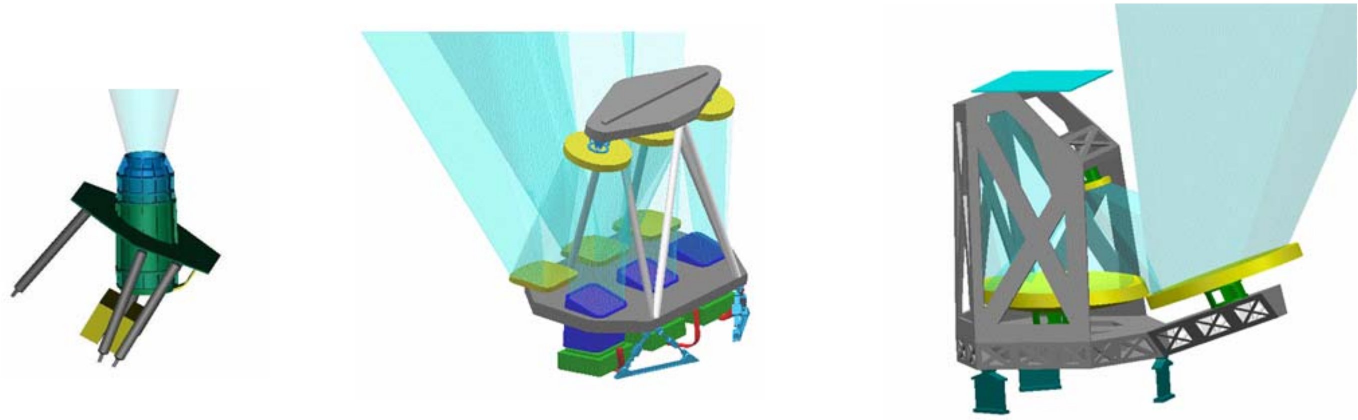
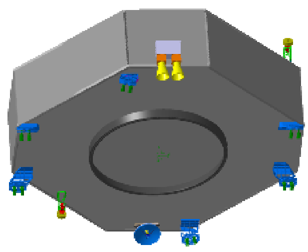


Figure 3-5 : Candidate optical concepts (from left to right: dioptric, catadioptric, catoptric) and focal plane geometries (driving the number and size of collectors) have shaped the configurations in the race. Criteria used to trade-off the candidate configurations include: mass, volume, power, collecting area, optical performance, science performance, design complexity, TRL and availability, growth potential, cost, and AIV aspects. We have used a Pascal matrix to apply weights on the selection criteria, and we have ranked the candidates. The dioptric solution (already proposed in CoRoT) outperforms the others, provides best science return, and is secure while allowing much flexibility.

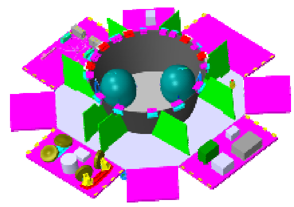
3.4 Service Module-Level Trade-offs



Platform concept (**new design** vs. **heritage**). After considering different platform architectures, a mechanical configuration conceptually derived from Herschel was selected, based on:

- octagonal panel structure surrounding a thrust cone, plus shear panels and lower + upper platforms,
- sunshield positioned on top of the SVM combined with body-mounted solar panels.

This is considered the most appropriate for an astronomical mission in L2 like PLATO due to:



- Compact and stiff configuration, suitable for Soyuz launch
- Re-use of existing s/s or slight modifications
- Large heritage on development, procurement and AIV/AIT.

Antenna pointing concept (**mechanical** vs. **electronic** antenna steering). The trade-off addressed 2 options:

- mechanically steered reflector antenna (high data rate, good mechanism TRL);
- electronically adjustable Phased Array Antenna (high data rate, high power consumption, higher cost).

The first concept as was finally selected; in particular, the solution consists of a feed/reflector HGA with steering mechanism capable of 8.72 Mbps in X-band with Reed-Solomon coding.

AOCS actuators (**reaction wheels** vs. **cold-gas thrusters**). Reaction wheels (RWs) are generally less accurate and characterized by higher power consumption. Nitrogen Cold Gas Thrusters (CGT) are penalized by mass (~35 kg additional propellant, equivalent to 50% more) and cost. RWs were selected as baseline actuators, mainly for cost reasons. CGT remain as back-up solution in case of possible future more stringent requirements.

3.5 Instrument Description

The PLM design includes:

- 54 staring cameras with identical field-of-view (625°²) and pupil diameter (83 mm) ;
- Spherical lenses[2], mounted on CeSic barrels ;
- 6000*6000 pixels per focal plane.

The cameras are shared in 2 groups because of science requirements:

- 48 (so-called “normal cameras”) are dedicated to the faintest stars (mv > 6.5) ;
- 6 (so-called “fast cameras”) are dedicated to the brightest stars (mv < 6.5) ;
- Normal and fast cameras only differ by their focal plane ;
- Among the fast cameras, two could be equipped with coloured filters (following science goal requirements), and optionally could stare a complementary field in order to improve performance on bright stars.

[2] We have baselined an optical design meeting image quality over the field with spherical lenses, and with optical materials identical to CoRoT. This choice secures planning and cost.

The payload involves 54 detection chains, which required thorough analysis during the study in the fields of detection, data handling, and electrical architecture.

The data processing is organized in 3 modules, each of them being composed by 18 cameras, 18 front-end electronics (FEEUs), 4 (3N+1R) data processing units (DPUs), and 3 power supply units (PSUs).

Two (1N+1R) instrument control units give data their final shape, and handle general interface with the SVM.

The overall payload was optimized to face stringent planning and cost constraints. Each camera can be integrated and tested as a single module and then integrated on the PLM, which is mainly a CFRP baseplate connected to the SVM by means of 3 glass fibre (GFRP) bipods. The payload electrical equipments are accommodated on top of the SVM

The strength of the present concept stands in its modularity and reliability. Commonality between cameras and associated electrical modules mitigate risk, planning and cost.

The budgets are compatible with system allocations:

- Mass = 834 kg (970 kg including margins) ;
- Power demand = 887 W (average), 952 W (peak) ;
- Output data rate = 892 kbps.

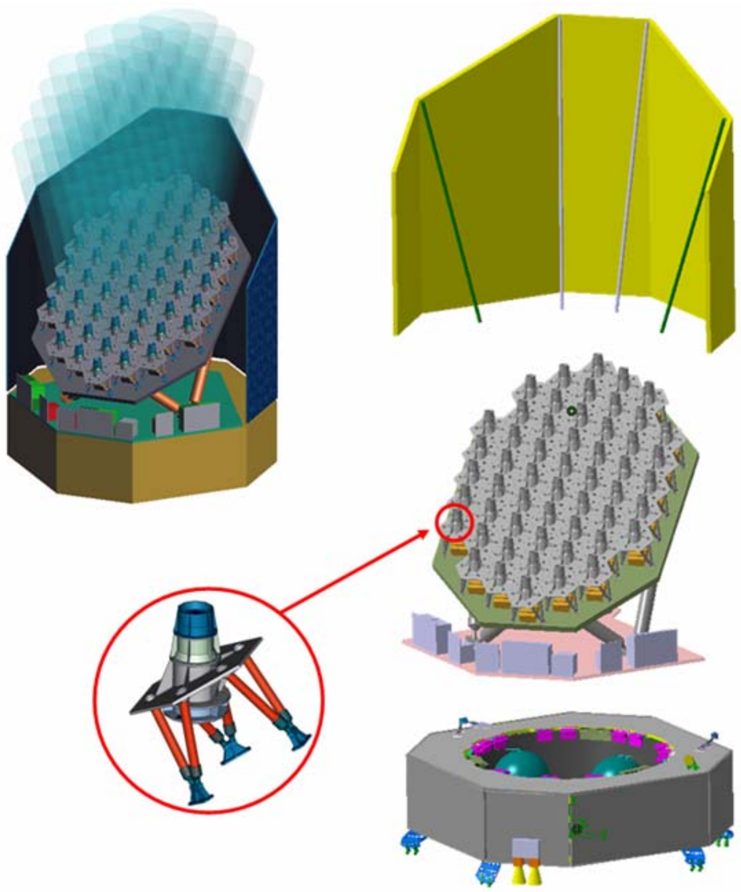


Figure 3-6 : 54 staring dioptric cameras are proposed, part of them being devoted to faint stars whereas the other part observes bright stars. This solution is very modular, and design choices secure risk and cost. Science performance criteria are met, and budgets are within system allocations.

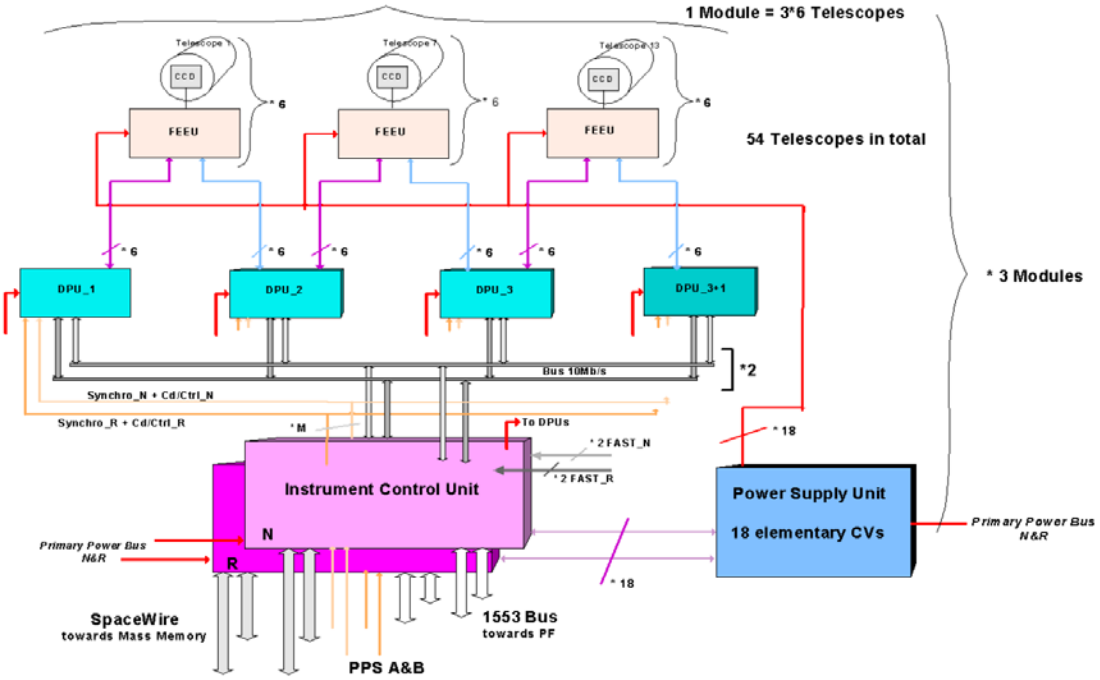


Figure 3-7 : Data handling and electrical architecture required thorough analysis. The outcome is a modular design, which results from a trade between power demand and redundancy philosophy.

3.6 Platform Subsystems

Structure: the mechanical configuration is conceptually derived from Herschel, based on:

- octagonal panel structure surrounding a thrust cone, plus shear panels and lower + upper platforms,
- sunshield positioned on top of the SVM.
- PLM on top of the SVM, supported by three bipods bolted to the thrust cone.

Data Handling: the on-board data handling is managed by a single unit (CDMU) performing the data handling functions, the attitude control and the thermal control.

The on-board communications are supported by MIL1553 bus for command and control, and Spacewire link for data science acquisition and storage. A centralized Mass Memory Unit (MMU) is used to record the Science data generated by the P/L. It interfaces with the P/L via SpW lines and with the CDMU via MIL 1553 bus.

TT&C: the TT&C has a classical X-band configuration inherited from other projects (Herschel, GAIA, Rosetta). It is composed by 2 transponders, 2 low-gain antennas and a steerable feed/reflector high-gain antenna with 0.3m diameter, plus two 35W Travelling Wave Tube Amplifiers and a distribution network (RFDN). Reed-Solomon coding is implemented to increase the DownLink data rate up to 8.72 Mbps.

EPS: it is composed by 6 GaAs/Ge body-mounted solar panels (3 on SVM + 3 on sunshield) providing 1700 W (EOL), a PCDU providing distribution and protection of the 28V regulated bus, and a Li-Ion battery designed to allow 55 minutes of attitude loss without power.

AOCS: it is composed by the following equipment:

- 2 internally redundant Sun Acquisition Sensors [SAS];
- Gyroscope Assembly [GYR], including four gyroscopes;
- 2 Coarse Rate Sensor Assemblies [CRSA];
- 2 autonomous Star Trackers [STR];
- Reaction Wheel System [RWS] including four wheels in a skewed configuration;
- Reaction Control System [RCS] (two branches of 6/8 20N monopropellant thrusters + n.2 tanks)

The AOCS operating modes foreseen for PLATO are:

- Sun Acquisition Mode (SAM);
- Science Mode (SCM);
- Orbit and Cruise Control Mode (OCM);
- Wheel Unloading (RWU);
- Safe Mode (SM).

For science mode the demanding requirement on attitude error spectral density (<0.5"/√Hz) calls for dedicated high-accuracy attitude measurement. This is obtained by using the payload data in the AOCS control loop. On board star catalogue is used to address the observation windows and for absolute attitude determination.

TCS: the SVM TCS makes use of SSM (Second Surface Mirror) coated radiators located on the anti-sun (-X) and on the lateral (+Y and –Y) panels. MLI blankets provide the necessary insulation of the non-radiating panels. MLI is also used on top of SVM for radiative insulation from the PLM, and on the bottom side of SVM. The internal enclosures are black painted for temperature homogeneity.

Thermal fillers/doublers or low conductivity standoffs are used for mounting equipments to increase or decrease the thermal coupling.

Active thermal control through heater lines can be actuated by the CMDU. For safe-mode operation a dedicated set of heaters is dimensioned to maintain units within their non-operative temperature range; these heaters are thermostatically controlled in order to be independent of software.

3.7 Budgets

The mass budget is 2093 kg including 20% system margin plus propellant and adapter, compliant with the requirement at launch (Soyuz-Fregat provides direct insertion of up to 2146 kg). The mass of the payload alone is approximately 1000 kg.

The power budget amounts to about 1700 W in science mode, compatible with the end-of-life performance of the 13 m² body-mounted solar array.

The payload data rate is < 1 Mbps, which means a maximum data volume of 110 Gbit/day including both Science and HK data and taking into account the contact duration.

4. PERFORMANCE

A dedicated Instrument Performance Model (IPM) was developed within the frame of this Assessment Study in order to verify the achievement of the scientific requirements, both in the trade-off phase to compare the different candidate architectures in terms of science return, and in the design consolidation phase to assess performance of the selected candidate. This tool strongly shaped the design, in particular when looking for the optimised way of sharing the collecting area between normal and fast cameras.

The main performance criterion for PLATO is the number of cool dwarfs observed with the required photometric accuracy. After the system performance evaluation by means of the IPM, the following conclusions can be drawn:

- Sample 1 and 2 target requirements are met or outperformed in 2 fields ;
- Sample 5 requirements are marginally met in 2 fields ;
- Sample 3 and 4 requirements are met provided that stars with magnitude up 8.5 are counted, and coloured cameras[3] observe a field complementary to the one observed by the main group of cameras.

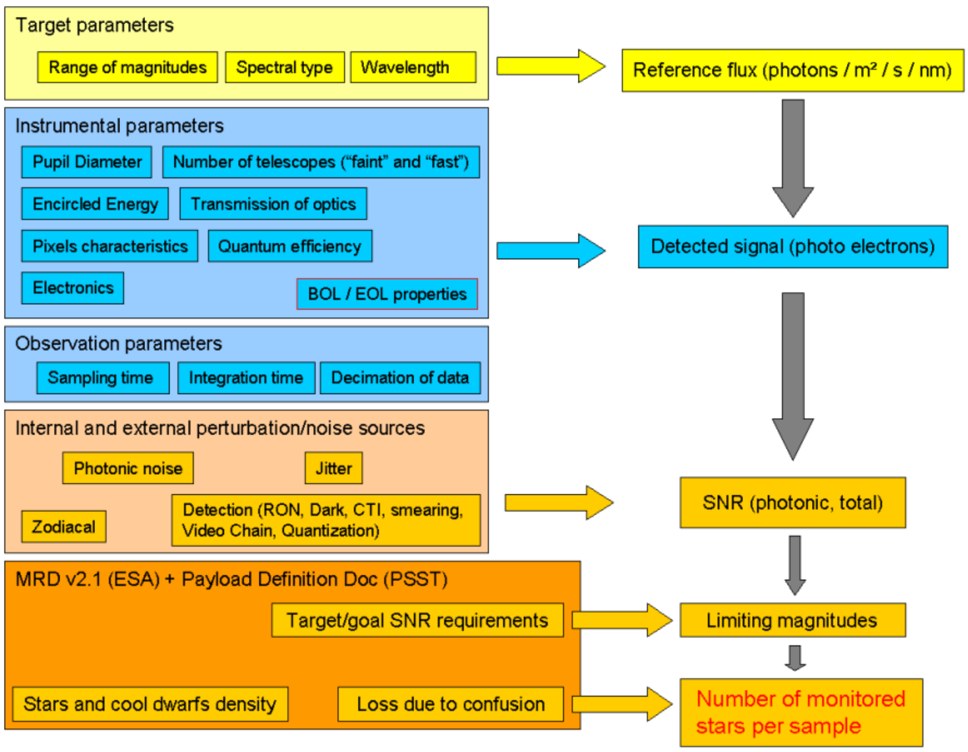


Figure 4-1 : The IPM is able to evaluate performance in terms of monitored stars per sample considering all photometric and non-photometric noise contributions (including the platform jitter contribution). Instrumental parameters have been set using measured data when available (transmission of optics, and ageing effects measured on CoRoT in-flight for instance), or design outputs (encircled energy, pixel size etc…). Other contributors may become specifications towards equipments later on (detection noises for instance).

[3] The goal science requirement has been implemented according to which coloured information should be provided on 300 stars.

5. DEVELOPMENT, AIV AND PROGRAMMATICS

The development and AIV plan proposed for PLATO has been conceived, taking benefit from the strong heritage from CoRoT, to secure TRL (Technology Readiness Level), cost and schedule requirements,

A modular concept is proposed (telescope assembly, PLM, sunshield, SVM) with simple and well-defined interfaces allowing as far as possible separate design, development and test of each module. The early definition of test requirements and necessary AIV /test tooling, as well as the selection of test facilities will be part of the design process, developed in commonality with other recent projects to benefit from design, development and test heritage.

The main development drivers include the schedule, constrained by early 2012 implementation start and end-2017 launch period, the procurement of the payload sensors and optics, subject to limited production rates, and the assembly and test of the 54 cameras, requiring most AIV activity to be carried out in parallel on different units.

After selection for mission implementation 4.5 years can be dedicated to the PLM development and production phases. This leaves more than 2 years for the procurement of all the equipment. Therein, anticipation of LLI (Long Lead Items) procurement and FM (Flight Models) manufacturing are identified as mandatory. Interaction with possible suppliers through RFIs (Request For Information) has been necessary for development and AIV plan consolidation. For each critical equipment the risks have been assessed and mitigation actions have been proposed.

The proposed system model philosophy consists of STM, EM/ATB (Avionic Test Bench) and PFM models at SVM, PLM and System level. STOM, QM's and FM's are instead foreseen at camera level.

This approach is driven by the CV schedule and is the best compromise between the supplier capability and the schedule targeted to end-2017 launch, which means a Payload Module delivery during the first half of 2016.

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