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1 INTRODUCTION

This report summarises the findings of the ESA internal review on the assessment study phase of the Cosmic Vision 2015-2025 mission candidate PLATO. The report entails the outcome of the review regarding technical and programmatic aspects. Three independent studies were performed in the scope of the assessment phase. Two parallel competitive industrial studies by Astrium (AST) and Thales Alenia Space (TAS), and one study by the PLATO Payload Consortium (PPLC) focusing only on the payload.

The review focused in particular on the payload segment of PLATO since this is foreseen to drive the mission in terms of complexity, cost and schedule. An overall assessment of the payload was done with the conclusion that the optical design, the CCD design and procurement as well as the mass budgets needed added reviewing effort due to their criticality to the PLATO mission. The platform segment (Service Module) is based on heritage from GAIA or Herschel depending on the Contractor and no mission driving critical issues were identified during the review.

The Board composition for the PLATO review is listed in the table below:

Table 1-1. Board composition of the PLATO review.

Mission Candidate (Review Cycle)	PLATO 2
Chair	Not available
Chair Deputy	G. Sarri
Secretary	R. Lindberg
Observers	F. Safa T. Passvogel R. Fontaine External observers
Thermal	H. Frueholz
Structure & Mechanisms	O. Piersanti
Optics	I. Escudero M. Erdmann
AOCS	B. Girouart
TTC / DHS	M. Suess
AIV/AIT	O. Piersanti
Focal Plane and CCDs	P. Gare
Programmatics	R. Tosellini

The full review team met 5 times during October 2009.

2 TECHNICAL REVIEW

2.1 Mission Aspects

Table 2-1 summarizes aspects of the mission relevant to completeness and consistency of the mission requirements, definition of responsibility and interfaces, design robustness and design verification. The table try to capture the risk of the mission to experience substantial changes in the design phase.

Table 2-1. Risk of experiencing a major design evolution in the Definition Phase.

Cause	Status	Risk level
Mission requirements	The mission requirements are reasonably well defined also thanks to the previous Eddington Phase B1 study. Flow down to engineering requirement shall be improved in Phase B1. One exception is the pointing stability for which the two studies show a different appreciation of the scientific need, leading to a different AOCS approach (cold gas micropropulsion vs reaction wheels). This is a design and cost driver and shall be re-assessed in Phase B1	Low
External Interfaces	External interfaces to ground are standard. In case, for funding reason, part of the S/C (likely part or the entire payload module) is to be provided by an external entity, no peculiar difficulties are identified in defining the relevant interfaces.	Low
Lack of design verification	The design verification at payload system level is not properly covered and may be underestimated. It is an important point to be addressed in Phase B1	Medium
Payload definition and interfaces	There are two different payload concepts: refractive vs reflective telescopes. The refractive system is technically feasible. There are concerns on the feasibility of the reflective system in the current configuration. In addition the reflective approach is more complex to implement and with a longer manufacturing time.	Medium (refractive system) High (reflective system)

2.2 Payload Module Design

2.2.1 CHARGE COUPLED DEVICES (CCD)

A comparison of the CCDs proposed for PLATO in the different studies with the Gaia CCDs was performed. The main characteristics of these devices are listed in Table 2-2.

Table 2-2: Comparison of GAIA CCDs with CCDs proposed for PLATO. Critical issues are marked in red.

	GAIA	ASTRIUM		THALES		PPLC	
Variant	**AF CCD**	**BM CCD**	**BS CCD**	**Normal CCD**	**Fast CCD**	**Normal CCD**	**Fast CCD**
Pixel size (µm)	10 x 30	27 x 27	27 x 27	18 x 18	18 x 18	18 x 18	18 x 18
Operating mode:	TDI	FFT	FT	FFT	FT	FFT	FT
Columns x rows (Phot. Area)	1966 x 4500	2080 x 2574	2080 x 1287	3000 x 6000	3000 x 3000	3584 x 3584	3584 x 1790
Die area (mm)	58.9 x 47.2	60.84 x 75.2	60.84 x 75.2	54 x 108	54 x 108	64.51 x 64.51	64.51 x 64.51
# of Output amplifiers	1	2	2	4	2	2	2
Readout frequency (MHz)	<1	2	2	1.8	2	2	2
Pixel Saturation level (e)	190 10^3	2 10^6	2 10^6	10^6	10^6	10^6	10^6
Antiblooming	No	No	No	Yes	Yes	No	No
Manufacturing: Wafer line Number of CCDs per wafer	5 inch line 2 CCDs per wafer	6 inch line 1 CCD per wafer		6 inch line ? 1 CCD per wafer (back-up 2 CCDsper wafer for normal camera [3000 columns x 3000 rows]). Novel improved full well capacity		6 inch line? 1 CCD per wafer. Novel improved full well capacity	
Deliverables (CCDs)	StM: 5 EM: 20 + 3 FM: 80 + 7 FS: 14 + 3 AF CCDs Blue CCDs	Mock-up: 5 + 15 BB: 2BM + 2 BS EM: 18BM + 4BS FM: 182BM + 10BS FS: 18 + 4 ?		EM: 4 Normal + 4 Fast FM: 96 Normal + 24 Fast FS: 4 cameras (3 Normal + 1 Fast)?		StM: 4 EQM: 4 N + 4 F e2v: 40EM? FM: 160 N + 8 F e2v: 200FM? FS:?	

All proposed CCDs are current state of the art and use already developed technology. It shall however be noted that the CCD configuration selected in the Thales and PPLC study foresee the use of a relatively high pixel saturation level for the pixel size (with antiblooming in the case of Thales). This technical choice is necessary due to the small pixels size. As a consequence the design and prototyping will present more of a challenge than for the configuration proposed in the Astrium study.

Given the high number of CCDs to be produced in all studies, a key element which will impact the spacecraft development is their manufacturing time. In order to evaluate the proposed schedules for the development and production of the potential PLATO CCDs, the GAIA CCDs development, manufacturing and test rate was used as a benchmark. In Figure 2-1 the time line of the GAIA CCD program is shown. Based on that, a reasonable production rate is about 3 CCDs per month.

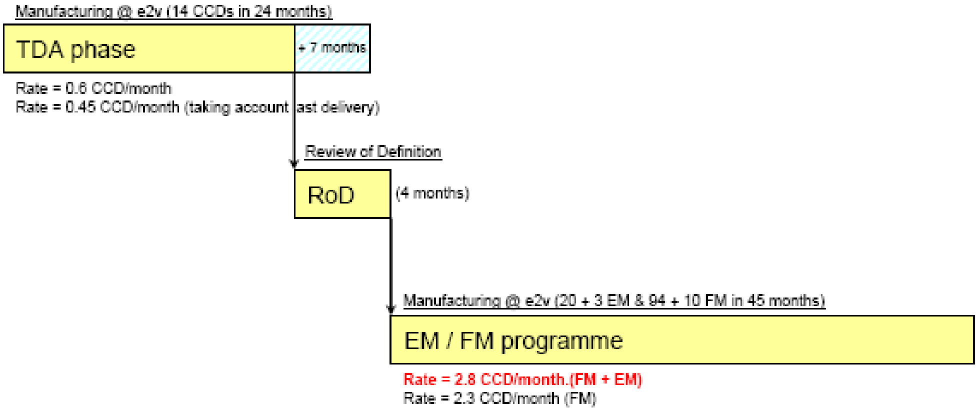

Figure 2-1: Time line of the GAIA CCD programme.

When the Gaia bench mark is applied to the two industrial studies and the PPLC the following schedule can be deduced for the Phase B2/C/D:

Astrium:	214 CCDs (BB + EM + FM + FS)	6 years
Thales:	128 CCDs (EM + FM)	3.6 years
PPLC:	168 CCDs (FM)	4.7 years

However it shall be noted that the Gaia benchmark is valid only for similar and validated CCD technology and processes, therefore:

- The ASTRIUM chosen CCD technology and process are similar to the Gaia benchmark. The ESA estimated schedule is thus realistic.

- The Thales and PPLC chosen CCD technology (18 µm^2& 10^{6}e FWC with or without antiblooming) departs from the Gaia benchmark. The ESA estimated schedule is thus less reliable and very likely underestimated.

In addition this assessment assumes that:

a) By the start of the Phase B2/C/D the selected CCD has been designed and few prototypes build to validate the design. This should take about one year and shall be done in Phase B1. If not one year more shall be added to the schedules above.
b) Immediate start of production of FM (EM devices being FM rejects) at the start of the B2/C/C phase.

2.2.2 OPTICAL SYSTEM

The optical design is the second most critical aspect of the design, therefore is discussed here in detail.Three alternative systems proposed by Astrium, Thales and the PPLC were studied. Their optical designs are shown in the three following figures. The scale bar is on the bottom right (200 mm in the Astrium figure and 50 mm in the Thales and PPLC figures). It is interesting to note the very different configuration between Thales and PPLC for the refractive design, i.e. much bigger cameras are proposed by the payload consortium.

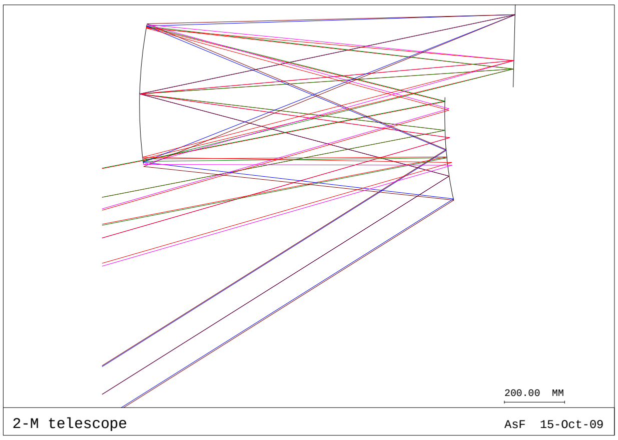

Figure 2-2: Astrium design with two mirrors.

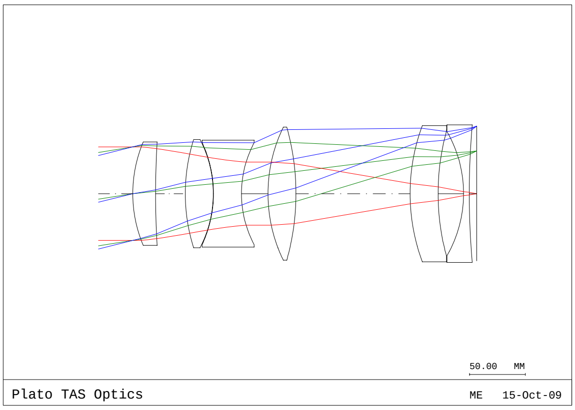

Figure 2-3: Thales design based on 6 spherical lenses.

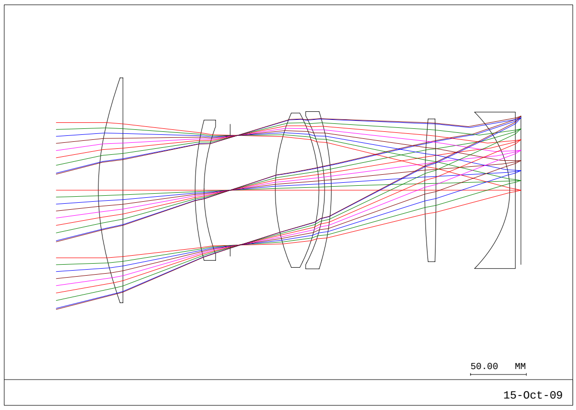

Figure 2-4: PPLC design based on 6 lenses of which two are aspheres.

A major feature of the proposed reflective design is that the mirrors shape is very difficult to manufacture. Oblate spheroids with high orders are used and there is a large departure from best fit sphere (M1: 1.129 mm). Tight mechanical tolerances are also required and adjustments will be necessary during integration.

The refractive design proposed by Thales is simple and compact but two aspects, radiation hardness and thermal performances and stability at low temperature are not properly accounted and my generated surprises in the detailed design phase.

The refractive design proposed by the PPLC generate more concerns associated to the size of the front lens (diameter is 200 mm) and the selected material (BaF2)

- Korth is biggest manufacturer in Europe: it would need 2 to 3 months to grow a BaF2 ingot of the required quality and size to cut 1 or 2 lens blanks. In addition Korth would have to update their facilities to cope with the lens size.
- Sensitive to thermal shocks but soft: required polishing control to avoid break.
- Hygroscopic (solvability: 0,17 g/100g @23°C) but it is controllable with appropriate environmental control
- Two aspherics lenses with difficult shape: conics with high orders and large departure form best fit sphere

The review team has assessed the production time for the two proposed concept. Gaia has been used as far a possible as bench mark for the reflective concept. More difficult is assessment of the refractive concept due to the lack of a reliable bench mark.

The reflective telescopes foresee 24 mirrors in SiC. Whether CVD coating can be avoided is not obvious. There are two types of mirrors, the primary or M1 has a very complex surface to obtain. The total area to polish is 5.6 m^2 which more that twice the total area of the mirrors in Gaia. A rough estimation of the time needed for completing one mirror M1 only is about 27 month. The secondary mirror M2 should be faster to produce. Assuming the mirrors are produced by two different companies and at least four can be done in parallel, the time to produce all M1 is more than 6 year.

The main issue of the refractive approach are the number of lenses to be manufactured - 250 to 300 depending on Thales or PPLC design- and integration/testing of the telescopes which has to operate in cold temperature.. Lens production schedule seems to be unfeasible as proposed unless the manufacturer has mass production capabilities or the production is split among several companies. Table 2-3 presents a summary of the main findings and recommendations on the presented optical concepts.

Table 2-3: Optical design assessment and recommendations.

<table>
<tr><th>Astrium</th><th>Thales</th><th>PPLC</th></tr>
<tr><td>Mirrors are very difficult. Some important technical risks not properly addressed.</td><td>Most promising design. All technical risks addressed.</td><td>Feasible, but testing of aspheres is open question.
Most technical risks addressed.</td></tr>
<tr><td rowspan="2">• Review concept design: Can aspheres be simpler? Other mirror material can reduce manufacture time?
• Review detail design:
• Include PSF/rms WFE error budget to assess mirror feasibility (manufacturing & testing)
• Include prototype in plans to: proof mirror feasibility & integration plans</td><td>• Review concept design:
• Replacement of front lens material or dimension entrance pupil according to end-of-life transmission losses.</td><td>• Review concept design:
• If aspheric term a4 can be included in K, testing might be simpler.
• Size of BaF2 front lens: will reduce production time.
• Review concept design:
It might be necessary to include thermal characterisation of opto-mechanical properties of glasses.</td></tr>
<tr><td colspan="2">Possible lens manufacturers: Rodenstock, Angènieux, Schneider Kreuznach, Leica, Zeiss.</td></tr>
</table>

2.2.3 DATA-HANDLING AND ELECTRONICS SUB-SYSTEMS

A/D Converter:

PPLC proposes the use of 16 bit ADC at a sampling rate of 4Msps. No specific component is identified in the documentation. There is a risk associated with the need to select and qualify of a new ADC for the PLATO mission. Thales and Astrium propose the AD7621 which has been "project qualified" for the Gaia mission. Nominally it works at 2 Msps but it supports also a fast sampling mode with 3 Msps. Still the performance is dependent on the frequency of the input signal.

Front-End Electronics:

The front-end electronics mainly contain the analogue function to control the CCD readout, the pre-amplification, the analogue to digital conversion and the management of the digital output interface. Only the Focal Plane Assembly with the CCD is held at low temperature while the FEE can be designed for a normal operation temperature range. PPLC and TAS foresee to have one FEE per telescope which has to operate all the CCDs of the telescope. Astrium on the other side uses one FEE per CCD. The FEE becomes simpler but 176 of them are required in the overall payload and have to be manufactured and tested.

Digital Processing Unit:

All three instrument concepts have a very similar hardware baseline for the DPU. Each of the three companies bases it on the Leon with some differences in its implementation. This allows to very well comparing the installed processing power per DPU. It is immediately apparent that the number of DPUs required by the different concept differs by a factor 5 to 10 while the average raw data rate differs only by 34% and the required processing step are about the same. At this stage of the study it is in general very difficult to have a good analysis of the algorithms which are not yet defined in detail. PPLC actually reports to have tested all the different processing steps and algorithms on a LEON simulator. Their processing requirement is therefore considered to be the most reliable one. If this is true then TAS and Astrium are seriously under estimating the required processing performance and hardware to be installed on board. If a significant increase is identified only at a later stage this will have a significant impact on the mass and power budget and therefore considered a major risk.

Payload Power Distribution:

PPLC locates the power conversion for the telescopes in the AEU close to the telescopes. In a similar way the power conversion at Astrium is implemented in the I2M inside the telescopes. In order to reduce the power dissipation in the front-end, TAS puts the DC/DC converter for the power supply of the FEEU placed in each Instrument Module. The 3 Power Supply Units (PSU), which contain a dedicated non redundant power converter board for each of the associated 18 FEEUs. Each FEEU requires 5 different supply voltages for which the 0V is grounded on the secondary side. This will lead to a quite complex power harness which is likely to have a significant mass. Still only an allocation of about 10% is budgeted for the harness mass with only 10% margin based on data derived from Herschel.

Digital Harness:

All three concepts use SpaceWire as standard digital interface between the telescopes and the DPU where the data are processed and compressed. PPLC and TAS use one SpaceWire link per each of the 42 or 48 telescopes respectively which will add up in quite a significant harness. Astrium concentrates the data for all CCDs in each telescope already in the I2M module and foresees one SpaceWire link for each of the 12 telescopes. This overall complexity and the generally high data rates have to be taken into account when assessing the harness mass and complexity.

2.3 Service Module Design

2.3.1 MASS BUDGET ASSESSMENTS

This section presents an independent estimation of the mass budgets for the different designs. The assessment uses the following assumptions:

- Spacecraft compatible with Soyuz-Fregat launcher
- Launcher adapter mass: 90 Kg (no margin)
- Maximum mass at launch: 2146 Kg (including adapter)
- Baseline scenario as proposed in the Consolidated Report on Mission Analysis i.e. large orbit around L2
- Re-visited Industry proposal and comparison with the actual mass of Herschel SVM (for TAS) and GAIA SVM (for Astrium)
- Considered: TAS proposal, Astrium proposal, PPLC design/concept
- A SVM as proposed by TAS has been considered for the PPLC design/concept
- Maturity margin for unit category A/B/C/D as per ECSS-E-ST-10-02C: 5% for A/B, 10% for C, 20 % for D
- System margin of 20% to be applied to the dry mass

The following tables give the estimated mass. For the Payload consortium the Thales SVM mass has been considered due to the similarity on the PLM design.

SVM Total	590.00
Sunshield total	145.00
PLM Total	970.00
Grand total	1,705.00
System Margin 20%	341.00
Dry mass with system margin	2,046.00
Propellant calculated wrt dry mass	85.00
Launch adapter	90.00
Launch mass	2,221.00

Requirement	2,146.00
Margin (+/-)	-75.00

TAS

SVM Total	670.00
PLM (including sunshield) Total	979.00
Grand total	1,649.00
System Margin 20%	329.80
Dry mass with system margin	1,978.80
N2H4	71.00
Cold gas	57.00
Launch adapter	90.00
Launch mass	2,196.80

Requirement	2,146.00
Margin (+/-)	-50.80

Astrium

SVM Total	590.00
Sunshield Incl. S.A. on it & radiator) total	160.00
PLM Total	1,098.00
Grand total	1,848.00
System Margin 20%	369.60
Dry mass with system margin	2,217.60
Propellant calculated wrt dry mass	85.00
Launch adapter	90.00
Launch mass	2,392.60

Requirement	2,146.00
Margin (+/-)	-246.60

PPLC with TAS SVM

All Mass Budgets result in a negative margin. The PPLC design, having the PLM with the larger mass, is the most critical for implementation. Considering the amount of missing mass, the mass saving should be implemented by reducing the size of the payload module and therefore of the spacecraft. To achieve compatibility with the Soyuz launcher, the required downsize is around 5%.

2.3.2 MECHANISMS

The TAS design foresees only one mechanism (the steearable HGA).

The Astrium design foresees 4 types of mechanisms: deployable sun shield, deployable solar array, steearable solar array and 2 steearable High Gain Antennas (2 HGA are needed as a result from the bi-annual rotation around the line-of-sight)

Even though the technology is not critical, mechanism development, qualification, reliability and operations are always schedule and cost drivers. They should be avoided if a possible system configuration allowing doing so exists.

2.3.3 ATTITUDE AND ORBIT CONTROL SUB-SYSTEM (AOCS)

Two main conclusions regarding the AOCS design for the different designs are that the same scientific requirements and consequently pointing and stability needs induced different design implementation for the AOCS. TAS is using Reaction Wheels (RW) as baseline as Science mode actuators. Astrium has chosen a micro-propulsion system (Gaia heritage). Considering the quite stringent RPE goals (for all time horizons considered in the studies, i.e. 25 s., 600s. and 14 hours), the compliance of a design with RW to the PLATO AOCS goal specifications for medium and long term (10 minutes and 14 hours) is not proved, in particular because the TAS place-holder for RW microvibration noise seems quite small with regards to typical figures and the telescope thermo-elastics evaluation is still preliminary. The compliance of a design with a micro-propulsion system is difficult to assess by direct benchmarking (14 hours is a quite unusual duration with regards to AOCS timeframes, 10 minutes is already quite large) but there is a good confidence that it should be feasible (Astrium budgets ignore system level contributors but a first order reconstruction of their real preliminary budgets presents a reasonable margin wrt current maturity of the design).

Two AOCS equipment units should be monitored during the next phase to ensure that appropriate TRL is met by the end of the Assessment Phase:

- cold gas microthruster (Astrium design) in case the current Gaia MPS features would not fit the PLATO need, e.g. wrt max thrust needed (this is not the baseline today but this might evolve in the next phase) - the risk is very low -
- Coarse rate sensor (TAS design): CRS (prototype) will fly as passenger on CRYOSAT 2 (but some issue with the demonstration foreseen) and are included in the sensor suite for Sentinel 3. This is not representative of PLATO environment and the TRL level depends on the Sentinel development. The risk seems low

All spacecraft concepts foresee to use data from the CCDs with short integration time (for observing the brightest stars) as input to the AOCS control loop. The noise level for the part of the payload being used as AOCS sensor is different in both industrial studies. This is probably linked to the payload design. This should be taken into consideration if SVM and PLM design are cross-used by both industries. Yet, the PLM sensors used for AOCS should be able to provide the expected level of performance for the currently defined Attitude Pointing Error (APE) and Relative Pointing Error (RPE – pointing stability). The information availability from the PLM sensor for AOCS (i.e. gap of information linked to star holes, sensitivity to solar flares) and the sampling time (time to transit from 1 group of CCDs to the other one, processing time…) are not studied in much details (or not documented?) which is understood considering the maturity of the studies. Still, these are drivers to discuss the need of a fine gyro for the Science mode. Refinements on these points are considered necessary before considering a gyro-less attitude estimation in Science mode as a baseline (see Astrium study).

2.4 Technology readiness

Table 2-3 summarizes the Technology Readiness Levels (TRLs) of the critical elements in order to be ready for a launch in 2017/2018.

Table 2-3. Technology Readiness with respect to 2017/2018 Launch.

Potential Critical Items	Maturity	Development Risk
CCDs	CCD are standard technology. Similar CCDs are being built for Gaia. However prototyping will be necessary. Issue will be the yield rate and therefore the production time.	Low
Front end electronics	Similar electronics is being developed and built for Gaia. FEE was development also in the frame of the Eddington study	Low
Processing electronics	Processing load lower than for Gaia. LEON 2 microprocessor baselined. LEON2 is already in production (LEON 3 not yet).	Medium
Optical system	Reflective system (Astrium) has complex shape primary mirror. Refractive system has simple, but large lenses. However there are potential thermal and radiation issues not yet properly investigated.	High (reflective) Medium (refractive)
High gain antenna	Heritage form earth observation. Mechanically stearable.	Low
Sun Shield	Heritage from Gaia (Astrium, deployable) Heritage from Herschel (TAS, fixed)	Medium (deployable) Low (fixed)
AOCS	Heritage from Gaia if micro propulsion system is selected (Astrium) Heritage form other S/C if RWL are selected (TAS)	Low

No particular development risk has been identified in the refractive system. However, should the refractive system be selected as the PLATO payload, further effort should be made in studying optimal methods of assembling optics in barrel segments and to ensure that the alignment accuracies can be achieved when the spacecraft commence science operations in cold (170K) environment (while launched in warm conditions).

A development and manufacturing risk for the primary mirror (M1) has been identified in the reflective system.

Early design and prototyping is recommended in Phase B1 to mitigate the schedule risk which has been strongly underestimated by the study. The following priority is suggested:

- CCD (mandatory)
- The M1 mirror (mandatory for the reflective system)
- One optical camera (lenses and barrel)
- Sun shield hold on and release mechanism

3 PROGRAMMATIC REVIEW

3.1 Development plan and schedule risk

Figure 3-1 shows the estimated schedule according to the findings of the review board, taking into account the CCD procurement estimates presented earlier in this report. This estimation assumes that the CCDs will be on the critical path.

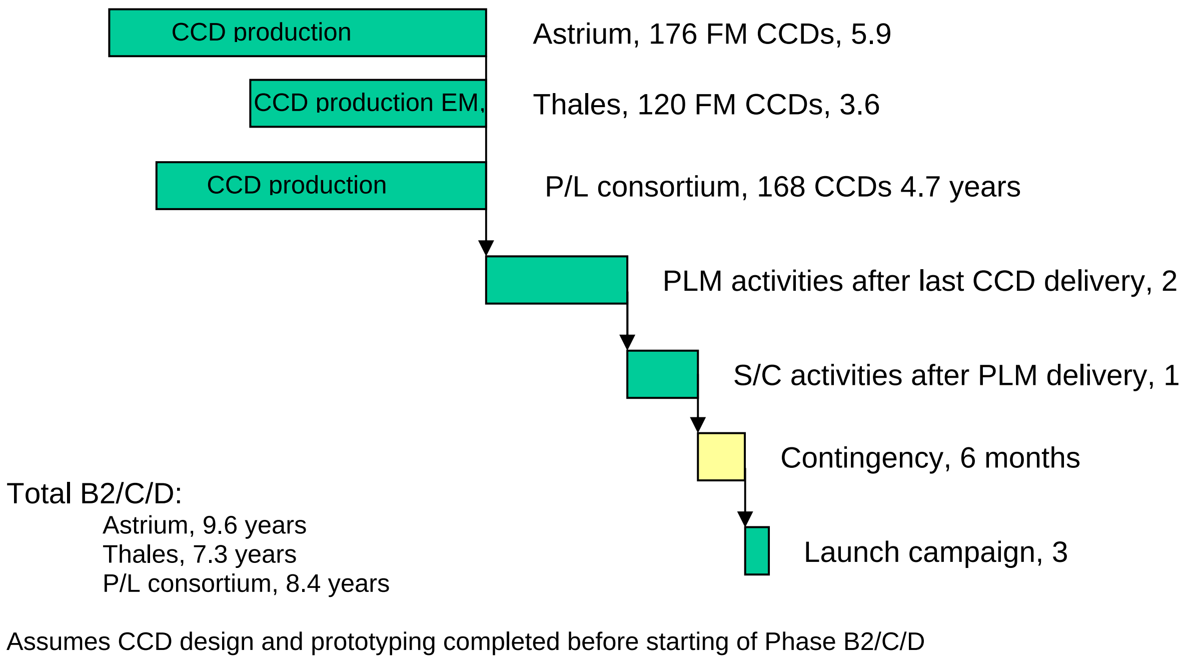

Figure 3-1. Estimated duration of phases B2/C/D for PLATO.

Based on the above and considering that, as explained in paragraph 2.2.1, the review team estimation of the CCDs production time for the Thales configuration is likely underestimated, a “realistic” S/C development time is 8.5 to 9.5 year. The driver is the huge number of CCD to be developed. In this analysis it is assumed that the optics (whether reflective or refractive) will take less time. This is still to be confirmed in particular for the reflective system.

The “realistic” schedule also assumes that the CCD design is frozen in Phase B1 and few prototypes are built, such that the EM/FM program can start immediately in Phase B2.

The only way to reduce the schedule is to reduce the number of CCDs to be manufactured, therefore the size of the focal plane and then of the payload module. The mission scientific performances may be reduced consequently if no recovery measures are taken.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The following summarises the main conclusions of the review team:

- The mission requirements are reasonably well defined to start the Phase B1.
- The spacecraft design does not show peculiar complexities beyond the state of the art achieved with Gaia and/or Corot. The mission is reasonably straightforward.
- The mass is underestimated. Compatibility with the Soyuz launcher requires downsize of the S/C by, at least, 5 %.
- The only identified critical technology is the manufacturing of the primary mirror M1 in the reflective system due to the very peculiar shape of the surface.
- The schedule is strongly underestimated. Main driver is the high number of CCDs to be manufactured (other elements are the high number of optical elements and the not fully thought verification at payload system level).
- Assuming start of the phase B2/C/D middle of 2012, a "realistic" launch date will be 2021. This assumes that the phase B1 is used to freeze the CCD design and prototyping; otherwise a further year shall be added.

4.2 Recommendations

The recommendation of the review team are summarised below.

Recommendations relevant to design and verification

- The refractive design is feasible. There are doubts on the reflective design due to the complexity of the mirror M1. The proposed refractive design (in particular that proposed by Thales) as has simpler optics, less CCDs and due to the observation strategy, less mechanisms. It should be considered as starting point for defining the reference design in Phase B1.
- To ensure a robust mass budget the size of the S/C (focal planes and number of telescopes) should be reduced by at least 5%. It will allow achieving compatibility with the Soyuz launcher.
- Freeze the design of the CCDs and prototype them in Phase B1 (at least one year necessary) such that phase B2/C/D can immediately start with the production of the EM/FM CCDs. Assess if the same is necessary for the optics.
- Review the verification approach at payload module level to assess the compatibility with the assumed schedule.

Recommendations relevant to programmatic aspects:

- The payload design and development will require a strong Prime with proven competence in complex optical systems and thorough involvement of space industry.
- The current design is not compatible with a 2017/2018 launch. To achieve end 2018 a major reduction (order of > 30%) of the payload module (number of CCDs and optics) is required. This would result in a positive mass margin, which can be used for increasing the pupil diameter and recovering at least part of the science performance. Considering mission extension in orbit could also help recovering performance. Using the ESA-developed instrument performance model for PLATO, preliminary results obtained by the study team at the end of the review indicate that the proposed way forward is viable with moderate impact on science performance if any.