DARWIN System Assessment Study

Summary Report

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1. INTRODUCTION

This report is the summary of the work done in the DARWIN System Assessment Study and presents its main results: selected concept and architecture, preliminary design, main performance at functional and interface levels.

This study has spanned around 12 months, featuring:

- a Phase 1 devoted to requirements review and architecture trade-of: it has led to the selection of the non planar arrangement;
- a Phase 2 devoted to preliminary design: together with the consolidation of the selected arrangement, it has produced the payload and spacecraft preliminary design, including performance budgets.

2. THE DARWIN MISSION

One of the next most fundamental issues for mankind will be the answer to the question of possible life in the universe: although this issue is definitely not new and dates back even to remote antiquity, because it is intrinsically human, the way to address it in a scientific way and using feasible techniques is quite recent.

Considering on the one hand the definition of life based on a biological and chemical approach involving specific spectral bands, on the other hand the technical state-of-the art of on-ground and spaceborne scientific missions, both ESA in Europe and NASA in the USA came to the conclusion that extraterrestrial life detection within the first two decades of the 21st century would be achieved only through either a coronagraphic mission operating at visible wavelengths and involving a large deployable telescope in space or an interferometric mission working in the nulling mode (cancellation of the stellar light by destructive interference) and involving a constellation of separate spacecraft (formation flying). The NASA approach, Terrestrial Planet Finder, features TPF-C for coronagraphy and TPF-I for interferometry, while the ESA approach focuses on the interferometry with DARWIN[1].

DARWIN mission objectives are thus detection and spectroscopic characterisation of Earth-like planets as primary mission, high resolution imaging by aperture synthesis as secondary mission. The primary mission dictates stringent requirements in spatial resolution and contrast ratio between star and planets, together with precision formation flying; this translates into unprecedented challenging requirements on Guidance, Navigation and Control (GNC) and down to nm level Optical Path Difference (OPD) control between the interferometer arms.

The mission feasibility was established in a system study conducted by Alcatel Alenia Space in 1998–2000: the proposed concept featured six Collector Spacecraft (CS), one Beam Combiner Spacecraft (BCS) and one communication spacecraft; as major output, the identified critical

[1] Detection of Alien Remote Worlds by Interferometric Nulling

technologies for further developments were implemented in the ESA's technology research programmes, which have brought a unique feedback on the achievable performance. In parallel, ESA has carried out studies which have led to reduce the number of collector spacecraft, in order to improve the affordability of the mission, and has found out a novel out-of-the plane arrangement , called Emma[2], with telescopes focusing the beams on the BCS instead of sending collimated beams towards the BCS from planar directions[3].

The new DARWIN mission study conducted by Alcatel Alenia Space in 2005-2006 takes benefit of this heritage: our proposed most promising configuration features three collector spacecraft and one beam-combining spacecraft in Emma arrangement, both maximising science return in terms of Signal to Noise Ratio (SNR) and sky accessibility, and dramatically alleviating engineering constraints thanks to a fully non deployable concept, significantly enhancing the system reliability.

The space segment main characteristics are as follows:

- Launch of the constellation on a single Ariane 5.
- Operation at second L2 Lagrangian point of the earth-Sun system.
- Operational spectral bandwidth: 6-20µm.
- Three telescopes in Emma arrangement[4], located at 1200m from BCS on the vertices of an orthogonal triangle, each vertex being itself located on a Virtual Parabola.
- Adjustable baseline between CS: 13-170m.
- CS primary mirror diameter: 3.15m.
- Freezing the constellation down to the nm level through four GNC and OPD control stages: one RF stage and one optical stage for spacecraft positioning down to the mm or the µm level depending on the metrology strategy adopted, then one optical stage for OPD control between arms, at last one optical stage as internal metrology.
- Passive cooling down to 40K of the optical benches, active cooling with a sorption cooler down to 7K for the detector.

3. SYSTEM TRADE-OFF

3.1 Possible architectures and trade-off rationale

Both Charles and Emma arrangements have been competing during Phase 1, each involving 3 or 4 telescopes located on dedicated free flyers, as sketched on Figure 3.1-1[5] (representation for 4 telescopes).

The trade-off rationale is summarised on Figure 3.1-2.

[2] from Charles Darwin's wife first name
[3] this conventional arrangement has been therefore naturally called Charles
[4] also called Three-Telescope Nuller (TTN)
[5] illustrations taken from ESA doct Darwin Science Performance Prediction, SCI-A/2005/300/Darwin/DMS

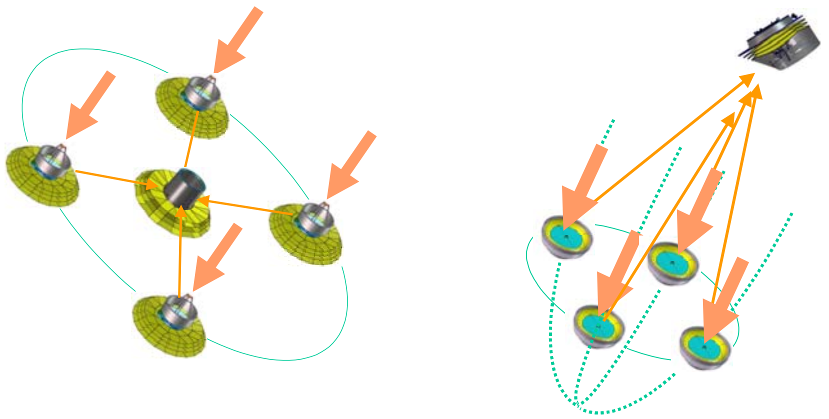


Figure 3.1-1 Charles (left) and Emma (right) lay on 2D and 3D arrangements

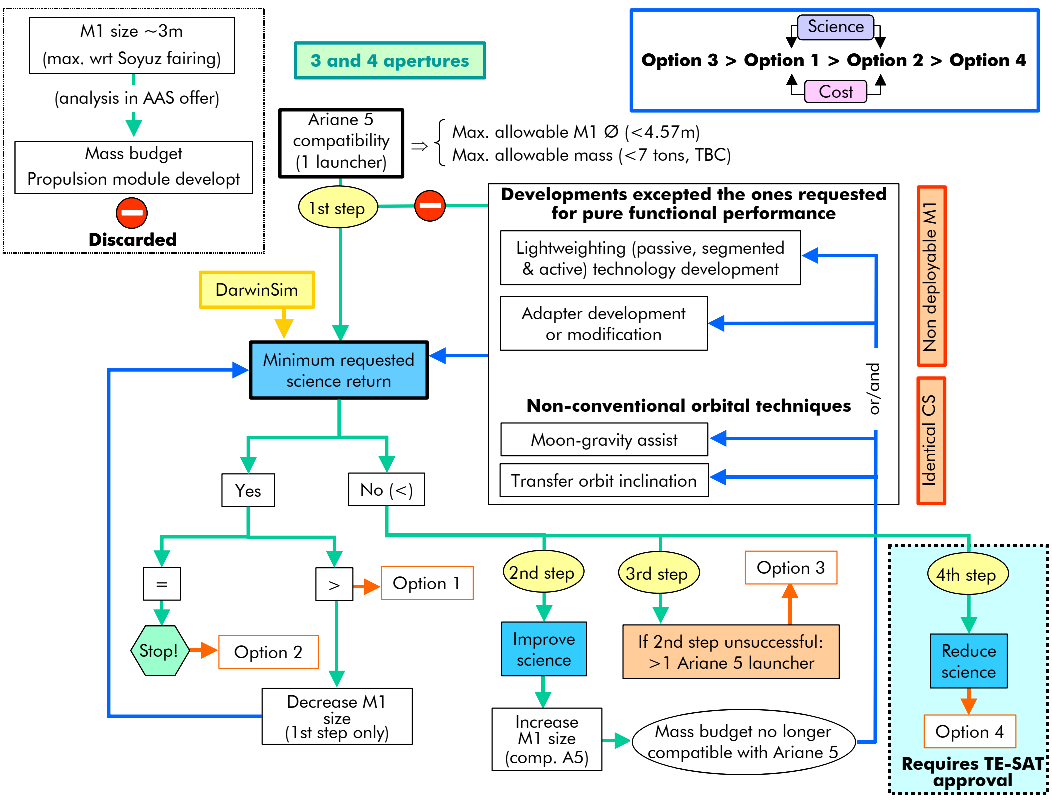


Figure 3.1-2 Trade-off rationale

For 3 or 4 apertures, four different configurations with two arrangements (Emma or Charles) have been studied:

- Triangular TTN: Equilateral or Orthogonal (3 apertures) (TE or TO TTN),
- Linear[6] TTN (3 apertures) (LT TTN),
- X-Array (4 apertures) (XA),
- Linear DCB (4 apertures) (LT DCB).

[6] Linear can be truly linear or semi-circular

3.2 Selected concept: Emma TO-TTN

Running ESA-provided DarwinSim on 12 possible architectures during Phase 1 has led to the ranking provided on Table 3.2-1.

Table 3.2-1 Architecture ranking

Relative rankings		A5 ECA				A5 ECB							
		3 apertures (TTN)				3 apertures (TTN)		4 apertures		3 apertures (TTN)		4 apertures	
		Emma		Charles		Emma				Charles			
Trade-off type		TO-TTN	LT-TTN	TO-TTN	LT+TO-TTN	TO-TTN	LT-TTN	XA	LT-DCB	TO-TTN	LT-TTN	XA	LT-DCB
ESA	Performance	7	5	11	12	3	4	2	1	8	6	10	9
	Cost & Risk	1	2	3	9	4	6	7	10	5	8	11	12
	Total	4	6	9	12	1	5	2	3	7	8	10	11
ESA with modified metrics	Performance	7	5	11	12	3	4	2	1	8	6	10	9
	Cost & Risk	2	3	1	4	6	9	10	12	5	7	8	11
	Total	1	2	4-5	10	3	8	6	7	4-5	9	11	12
AAS	Performance	6	4	11	12	1	4	2	2	9	7	10	8
	Cost & Risk	1	3	6	11	2	5	4	7	7	10	9	12
	Total	2	4	7	12	1	5	3	6	8	9	9	11

1st solutions

Cheapest solutions

2nd (and 3rd if close to 2nd) solutions

Most performing solutions

1st ranked Charles solution

2nd ranked Charles solution if close to 1st

This table highlights the following points:

- Emma arrangement is always superior to Charles arrangement in terms of science return.
- Emma TO-TTN with A5 ECB emerges as the best solution, but Emma TO-TTN with A5 ECA is more appealing when it comes to cost.
- Looking for the best science return makes LT-DCB with A5 ECB emerge at first place, closely followed by XA with A5 ECB.

Therefore:

- Emma TO-TTN with A5 ECA has been taken as the baseline to be subjected to the Phase 2 design exercise. This solution combines the advantages of high science return and low cost: should A5 ECB be decided, an additional margin would be provided.
- Charles TO-TTN with A5 ECA has been considered as a backup to be switched to at mid-Phase 2, should Emma lack of maturity compared to Charles translate into higher complexity or even raise achievability concerns. Phase 2 design activities have definitely confirmed that Emma features no show-stopper, hence confirming the Emma TO-TTN with A5 ECA as the best solution.

3.3 Possible alternative: Emma X-Array

Owing to its potential interest should some system constraints be relaxed (for instance availability of a dedicated propulsion module) so as to allow for some increase of the collector diameter (limited to around 2m with the present system constraints), an alternative Emma-XA solution with 2.5m collectors has been envisaged and could indeed be highly promising: Figure 3.1-1 (right) represents such a deployed configuration.

4. SCIENCE PERFORMANCE

4.1 Modulation map

Nulled outputs and modulation map are provided on Figure 4.1-1, modulated signal as a function of the detected planet orbital radius on Figure 4.1-2.

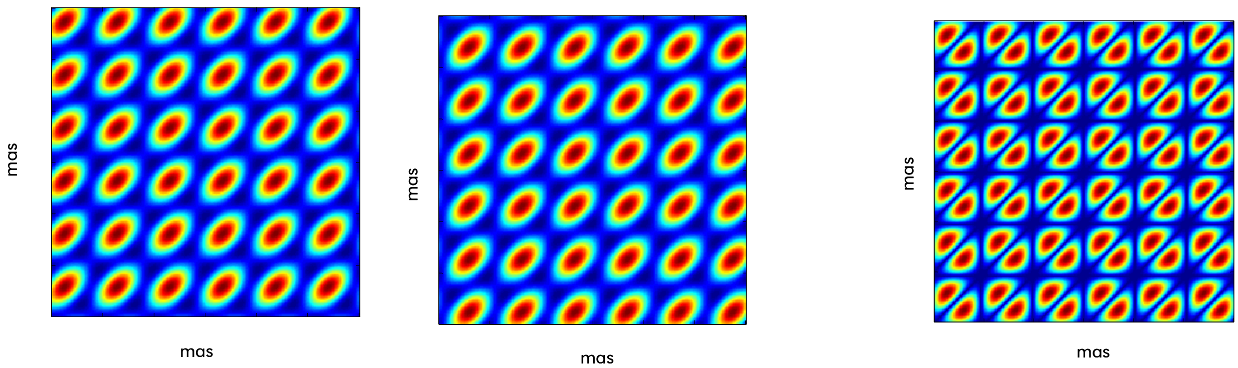


Figure 4.1-1 TO TTN nulled outputs (left) and modulation map (right)

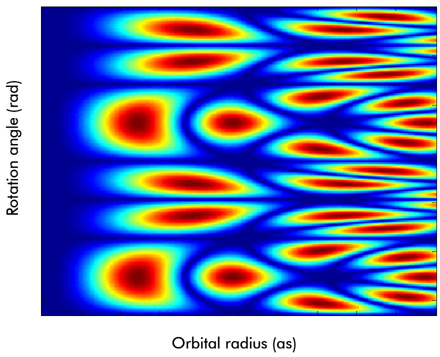
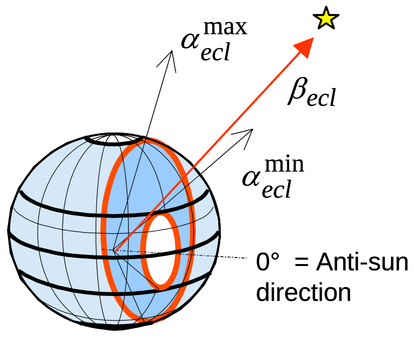


Figure 4.1-2 TO-TTN modulated signal as a function of planet orbital radius

4.2 Sky accessibility

One key difference between the two Charles and Emma arrangements, inherent to the concepts independently of accommodation constraints is related to sky accessibility: straylight and thermal constraints dictate specific relative positioning of the S/C w.r.t. the Sun and the stars.

Charles sky accessibility is straightforwardly derived from simple geometrical constraints, leading to an allowed cone whose axis is the one linking the Sun to the centre of the constellation and the angle is dictated by the sunshield size. Owing to allowed Solar Aspect Angle w.r.t. straylight and thermal constraints, Emma sky accessibility features two embedded cones (one allowed cone and one exclusion cone) as represented on Figure 4.2-1.



- α_{ecl}^{min} : solar aspect angle between Sun direction and anti-star direction – minimum value
- α_{ecl}^{max} : solar aspect angle between Sun direction and anti-star direction – maximum value
- β_{ecl} : ecliptic latitude of the science star target

Figure 4.2-1 Specificity of sky accessibility with Emma

Table 4.2-1 shows the different parameters used to quantify the sky accessibility. For comparison, values are given for both arrangements Emma and Charles.

Table 4.2-1 Sky accessibility parameters shows best performance for Emma

	Emma	Charles
Sky coverage (or yearly sky access.)	$\alpha_{ecl}^{max} = 83°, \forall\ \alpha_{ecl}^{min}$ → **99.25%**	$\alpha_{ecl}^{max} = 45°, \forall\ \alpha_{ecl}^{min}$ → 70.7%
Instantaneous sky access	$(\alpha_{ecl}^{min}, \alpha_{ecl}^{max}) = (46°, 83°)$ → **28.6%**	$(\alpha_{ecl}^{min}, \alpha_{ecl}^{max}) = (0°, 45°)$ → 14.6%
Yearly maximum available obs. time for 1 science star	See plot hereinafter for: $(\alpha_{ecl}^{min}, \alpha_{ecl}^{max}) = (46°, 83°)$	See plot hereinafter for: $(\alpha_{ecl}^{min}, \alpha_{ecl}^{max}) = (0°, 45°)$

Figure 4.2-2 presents the maximum available observation time over one year.

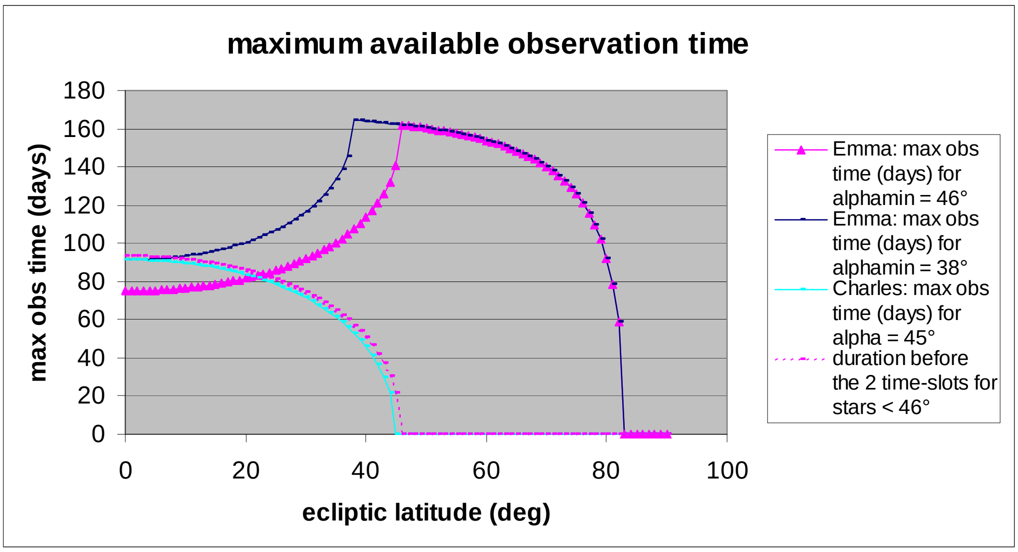


Figure 4.2-2 Yearly maximum available observation time

4.3 Mission performance

Figure 4.3-1 summarises Emma TO-TTN detection performance as they were presented at Mission Baseline Review together with similar sets of curves for spectroscopic performance.

Performance were calculated using DarwinSim v3.3 and the Darwin target stars catalogue, including M-type stars.

Observation parameters (Duty Cycle, mission lifetime, minimum SNR's required) were set according to ESA requirements in AD1. Time allocations were set depending on spectral type: 10% time for F-type stars, 50% for G-type stars, 30% for K-type stars, 10% for M-type stars.

Based on these simulations, the requirement for useable M1 diameter (i.e. not necessarily the physical diameter) was set to 3m, because it stays within an A5 launcher capabilities, while reaching science performance requirements:

- 150 stars screened and 15 planets characterised during nominal mission lifetime (5 years), assuming 10 zodi clouds around those stars ;
- 225 stars screened and 22 planets characterised during nominal mission lifetime assuming 1 zodi clouds around those stars.

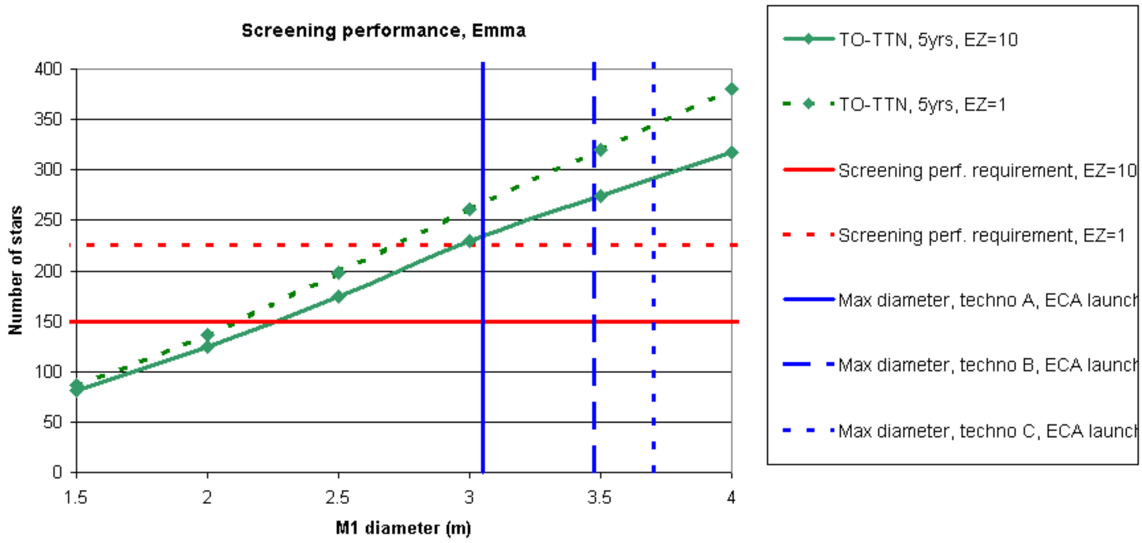


Figure 4.3-1 Screening performance achieved by Emma TO-TTN

5. ARCHITECTURE BASELINE

5.1 Overview

Emma Triangular Orthogonal Three-Telescope Nuller (TO-TTN) configuration (with a ratio of 1 between orthogonal sides) features 3 Collector Spacecraft (CS) and 1 Beam Combiner Spacecraft (BCS): it has been selected during Phase 1 for its quite superior performance in terms of science return w.r.t. to Charles (planar) configuration (for same diameter telescopes), and taking account of Ariane 5 accommodation constraints precluding the implementation of 4 large size (>2.5m) telescopes as well ESA constraints related to the minimisation of non proven technologies or orbit injection operations. Each CS is equipped with large diameter (around 3m) spherical mirror sending the scene light back towards a focal point located in the vicinity of the BCS, at around 1200m. The CS are located on a same plane perpendicular to a virtual paraboloid: their distance vary between around 20 and 170m according to mission needs translated into different baselines.

The core of the BCS is the Beam Combiner Assembly (BCA) with several optical stages aiming at collecting the CS beams then routing (and correcting them in terms of WFE & OPD) to a recombination stage producing the interferometric output: only nulling interferometry has been considered, but provisions have been taken for a possible imagery mission. For each target star, the CS rotate around the target star oriented axis, while the BCS remains fixed: this particular configuration, justified by the necessity to minimise the size of the sunshields in the Emma arrangement, affords fixed V-Grooves and sunshields both on CS and BCS, dramatically reducing the number of SPF and thus increasing the reliability of the mission as compared with the more conventional planar arrangement requiring large deployable V-Grooves and sunshields; it also affords a significantly lower straylight rejection than the planar configuration.

Emma features a specific metrology subsystem involving a three-stage set of RF and optical sensors, coping with formation flying requirements and ensuring a challengingly low level of OPD in terms of value and stability, constrained by Variability Noise which imposes to implement an internal metrology stage after the first three correction stages.

The BCA features transfer optics, a correction stage (involving tip-tilt mirrors, a deformable mirror, a DWARF-type Fringe Sensor and an Optical Delay Line), a modulation device, a spectral separator (splitting the 6-20μm waveband into three sub-bands), Modified Mach-Zehnder optics, Achromatic Phase Shifters, Single Mode Waveguides and a spectrometer. Detection is ensured by BIB detectors cooled down to around 8K through a sorption cooler. Multiaxial recombination has been selected owing to its higher overall efficiency (associated to the chosen dual output scheme) and expected superior performance in background rejection.

An artist view of Emma is provided on Figure 5.1-1, while Figure 5.1-2 provides Darwin space system block-diagram.

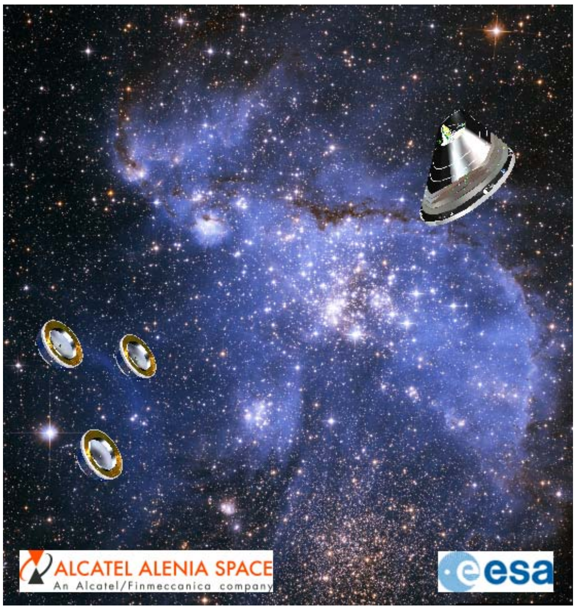


Figure 5.1-1 Emma artist view

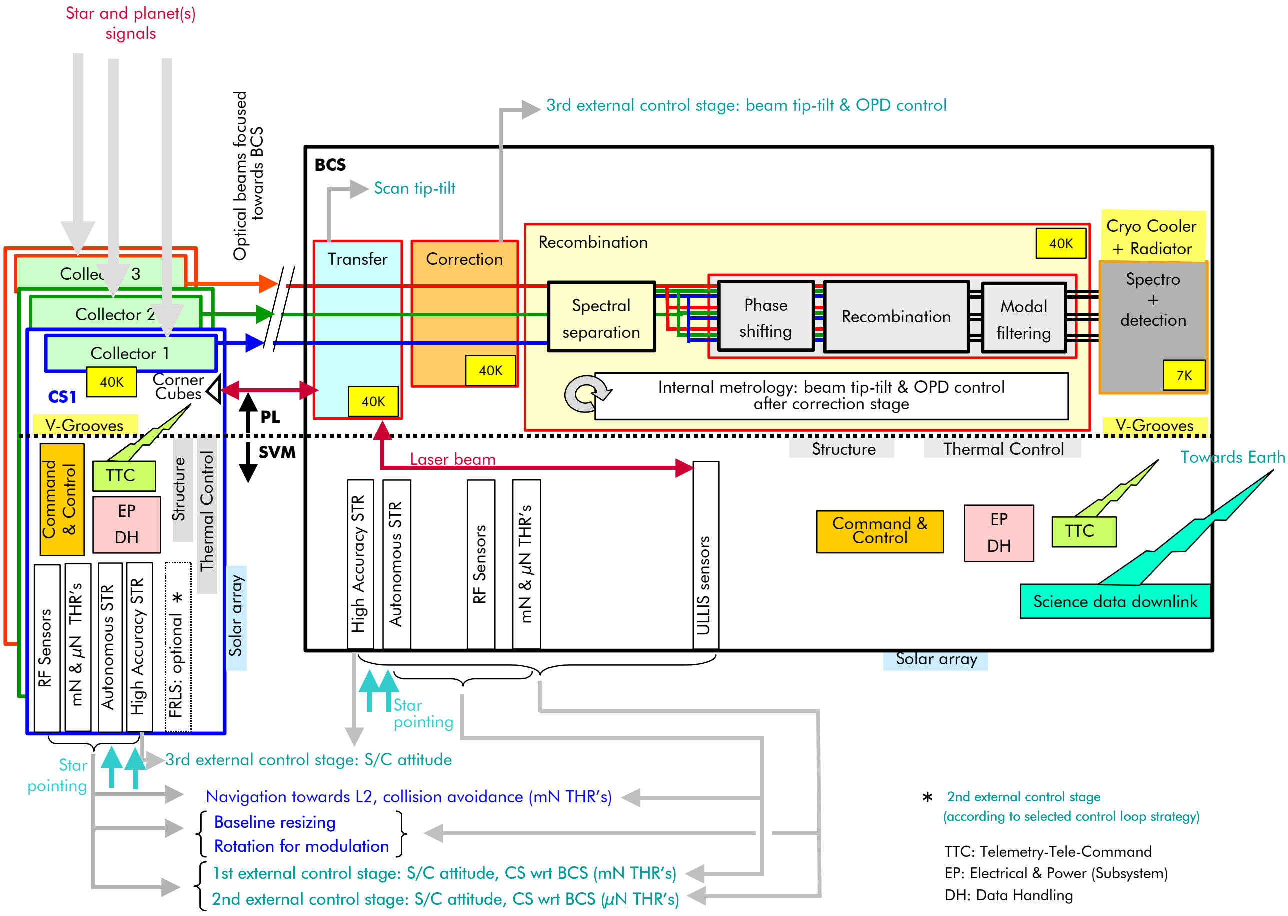


Figure 5.1-2 Darwin space system block-diagram

5.2 Payload description

From a functional point of view the Darwin optical instrument must have a number of systems able to fulfil several basic optical functions illustrated on Figure 5.2-1.

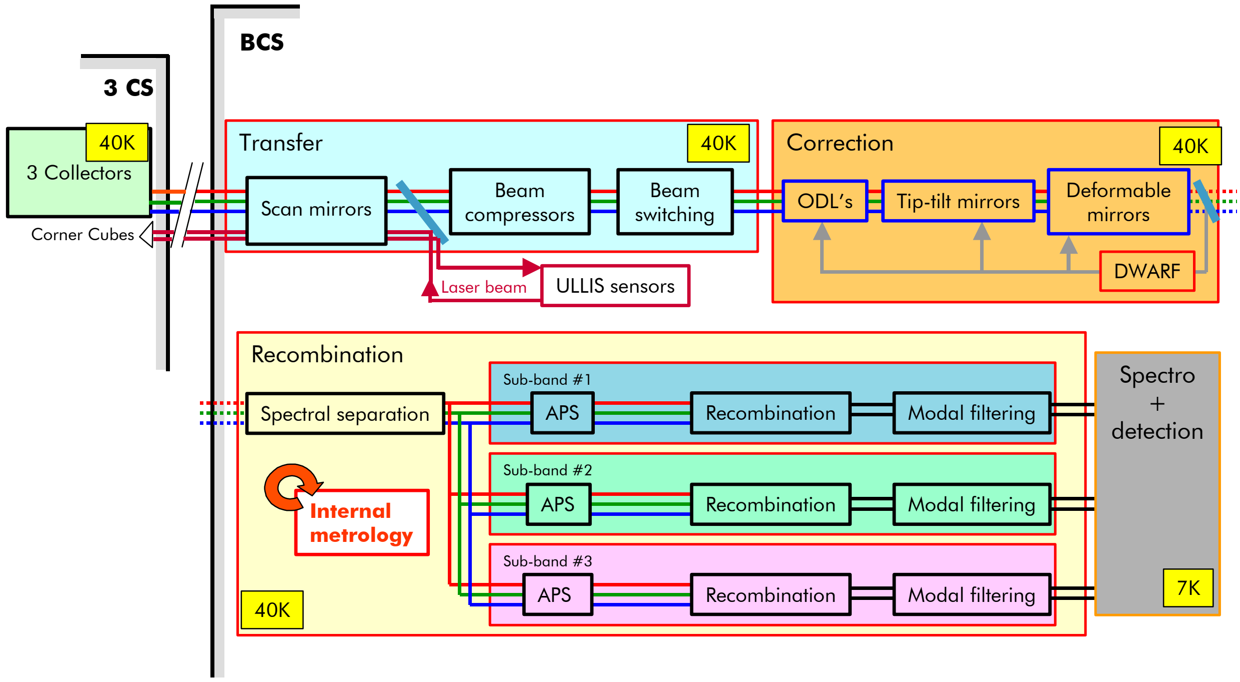


Figure 5.2-1 Payload functional chain

Collecting mirror diameter is set by minimum science requirements (they are met starting from 3m collectors), plus slight oversizing aiming at relaxing GNC requirements and straylight issues.

The use of spherical primary mirrors leads to defocus and astigmatism that vary with the collector distance from the Virtual Parabola (VP) axis. These effects are fixed for a given baseline, and are compensated partly locally, and partly thanks to deformable mirrors located into the combiner.

CS collecting mirrors focus the beams at the VP focal point. Due to extremely low f-number (near 300), the BCS is placed several tens of metres from the focus in order to avoid near-focus effects.

The distance between CS and BCS results from the VP's focal length and the distance of the BCS from the CS focal plane. VP's focal length has been set to 1.2km. It has been traded-off versus differential polarisation effects and inter spacecraft metrology capability, as well as implementation of longer baselines for imagery mode.

Inside the BCS, the BCA (Beam Combiner Assembly) receives 3 diverging beams. They pass through the following steps up to the detection:

- Transfer optics redirect them towards fixed directions whatever the interferometer configuration. Optical combination is optimised (in particular incidence angles) so that differential polarisation effects are negligible. Beams are then collimated and compressed by a factor of about 2.5. This optical stage houses also passive optical sensors (ULLIS[7]) for inter satellite optical metrology.
- The beams are then equalised and corrected by Optical Delay Lines (ODLs), fine pointing mirrors and deformable mirrors located on the correction stage. On this stage also lay the OPD and WFE sensor based on the same principle as DWARF, as well as a beams switcher device.

Collector and BCA are schematically represented on Figure 5.2-2 and Figure 5.2-3 respectively.

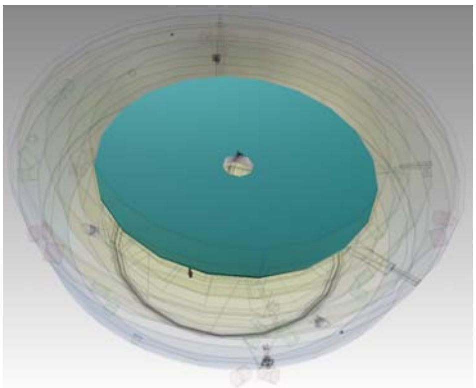


Figure 5.2-2 Collector view

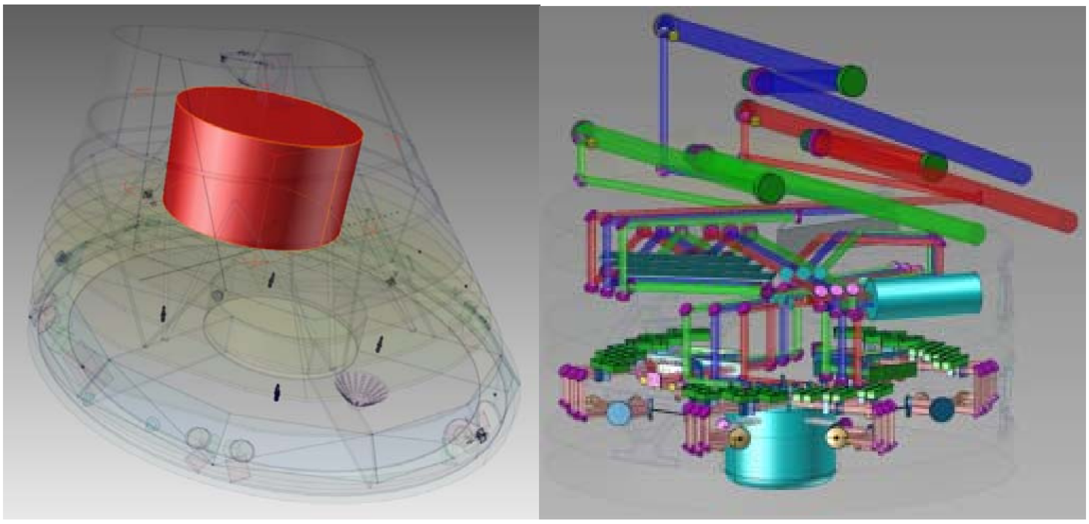


Figure 5.2-3 Volume allocated to the BCA inside the BCS (left), and split view of the optical payload (right)

[7] Universal Longitudinal and Lateral Instrument Sensor

The beams are spectrally split into 3 sub-bands with equal relative bandwidth. This splitting derive from considerations on coatings manufacturing, as well as acceptable chromatic coupling loss from side to side of each sub-band (Figure 5.2-4).

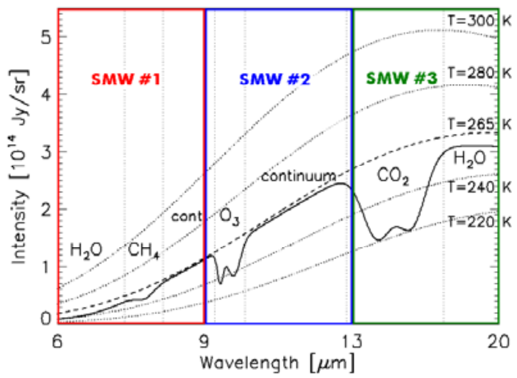


Figure 5.2-4 Spectral sub-bands proposed

Prior to the recombination stage, beams are mixed so that constructive and destructive outputs can be provided simultaneously according to the so-called dual output arrangement proposed by ESA for 3 telescopes nullers. The principle is illustrated on Figure 5.2-5.

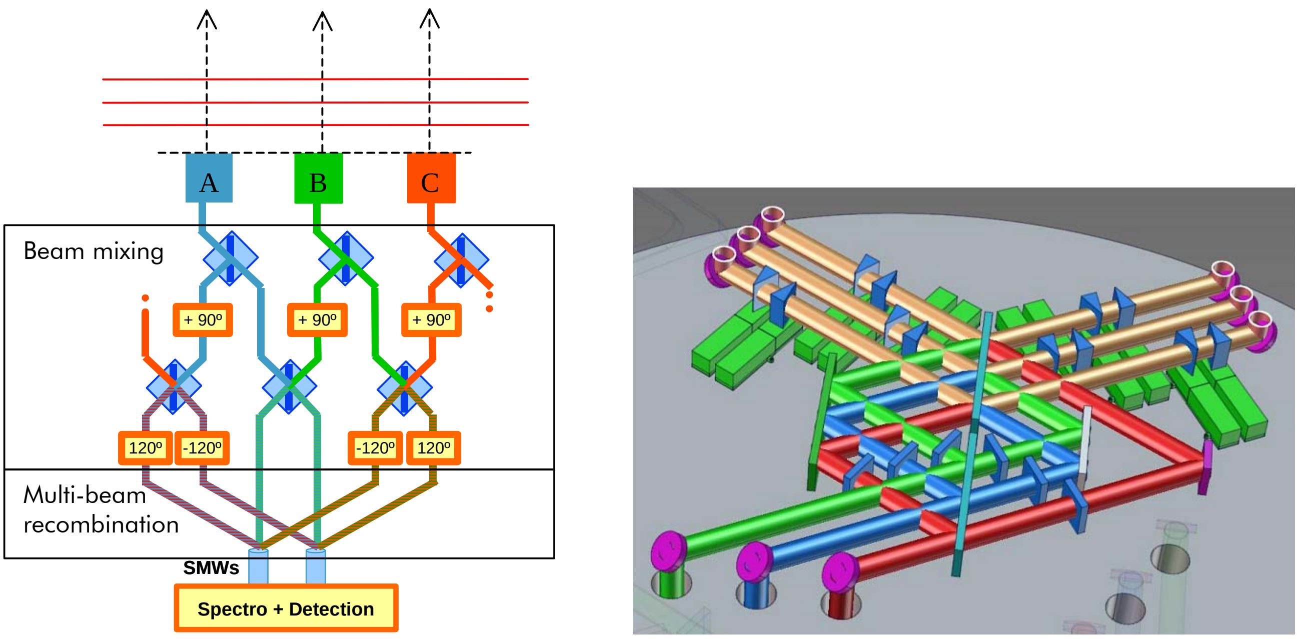


Figure 5.2-5 Dual output beams scheme (left) and accommodation of beams mixing on Darwin payload (right)

For each sub-band, the two complementary sets of beams are then focused by on-axis parabolas onto SMW's according to the multi-beam injection method. Outputs are spectrally dispersed for science needs prior to detection.

5.3 GNC and OPD control

5.3.1 The three GNC and OPD control stages

Three levels of control have been defined:

- **First external** control stage: coarse stage based on milli-propulsion thrusters (THR) and on the measurements delivered by RF Sensor (see Figure 5.3-1) and autonomous Star Tracker (STR).
- **Second external** control stage: aims at reaching a sub-millimetric control level; it is based on optical laser sensor (ULLIS) and a High Accuracy Star Tracker (HAST and involves micro-propulsion thrusters.
- **Third external** control stage: consists in the OPD and tip/tilt control loops; it uses the measurements of a Fringe Sensor (FS) and actuators as Optical Delay Line (ODL) and tip/tilt (T/T) mirrors.

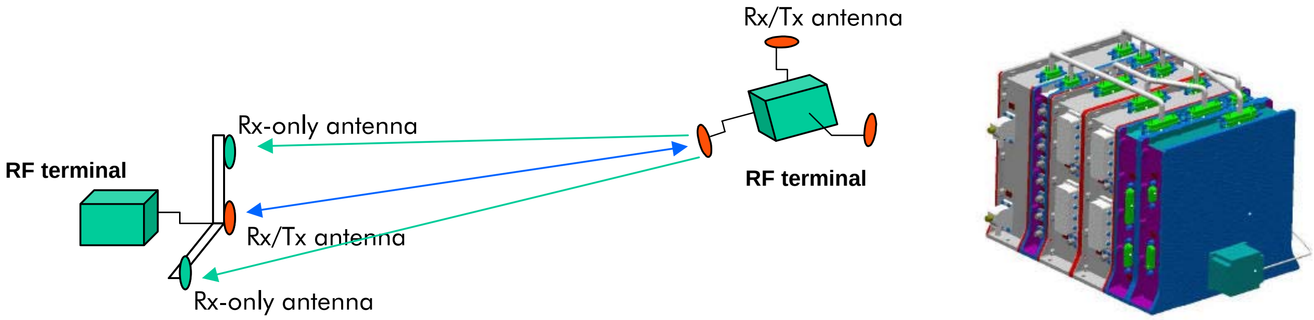


Figure 5.3-1 RS Sensor principle and view of the unit

For the 2nd external control stage, two strategies are proposed:

- Strategy 1: 2nd & 3rd stages in closed loop → Use of an additional sensor for the 2nd stage (Fine Relative Longitudinal Sensor FRLS); the benefit is an increase of mission Duty Cycle.
- Strategy 2: 2nd stage in open loop (let drift the S/C relative position) + 3rd stage in closed loop → 2nd stage only used for fringe acquisition and ODL unloading; the observation duration is then linked to 3rd stage actuators (ODL) range and CS primary mirror oversizing.

First external control stage (see Table 5.3-1):
During all operations of the 1st control stage (based first on coarse then on fine RF Sensor mode), the BCS keeps free flight on its orbit in the vicinity of L2 and operates only orbit control manoeuvre if necessary. The nominal formation flying is done by the CS positioning w.r.t. BCS. The control is done in a decentralised manner since the RF sensor measurement is directly available on each CS.

Table 5.3-1 First external control stage equipments

RF Sensor	Acquisition range: up to 100km; fine accuracy: $\Delta r = 1\text{cm}$, $\Delta\theta = 1°$, $\Delta\dot{r} = 1\text{mm/s}$, $\Delta\dot{\theta} = 0.01°/\text{s}$
Autonomous STR	Acquisition of inertial attitude (Lost in Space capability), performance compatible with the acquisition of the HAST used by the 2nd external control stage. On BCS & CS.
mN ion-THR	12-thruster configuration (+6 thrusters for redundancy). Max Trust per THR: 20mN. On BCS & CS.

Second external control stage (see Table 5.3-2):
The objective of the second external control stage is to improve the control accuracy of the formation in order to be compatible with:

- no loss of intensity in the transmission of scientific beam from CS to BCS (thanks to sufficiently accurate pointing and relative positioning),
- the acquisition conditions of the Fringe Sensor,
- the strokes of the ODL and tip/tilt mirror.

For the Normal Observation Mode, two different strategies are possible. In both cases, the 3rd control stage works in closed loop, the difference is only relevant on the use of the 2nd control stage. Both solutions are summarised on Figure 5.3-2.

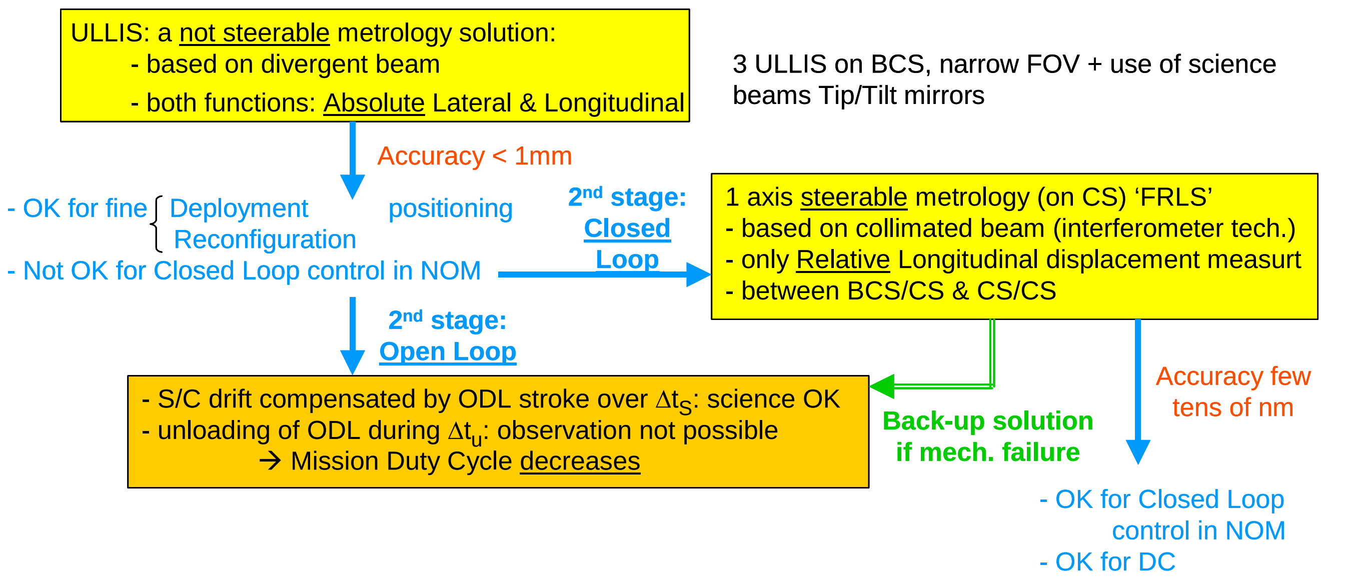
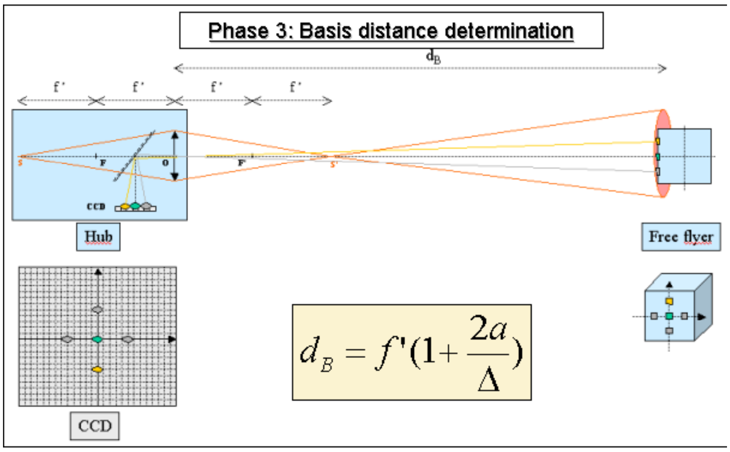


Figure 5.3-2 Proposed control solutions during observations

Table 5.3-2 Second external control stage equipment

ULLIS (see Figure 5.3-3)	Absolute lateral & longitudinal measurements functions embedded in same unit: acquisition range up to ±10°. Accuracy <1mm for longitudinal and better than 100 µm for lateral.
HAST	Few degrees Field of View: 0.5as at 2Hz is achievable. On BCS & CS.
FRLS	Fine Relative Lateral Sensor. Only displacement measurement. Noise: $tens\ nm/\sqrt{Hz}$
μN THR	12-thruster configuration (+6 thrusters for redundancy). Noise: $\approx 1\mu N/\sqrt{Hz}$. On BCS & CS.



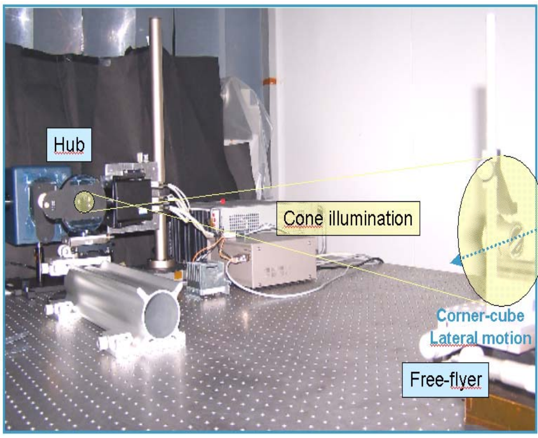


Figure 5.3-3 ULLIS principle & overview of the breadboard

Third external control stage (see Table 5.3-3):
The third external control stage, only implemented on BCS, is the ultimate control stage before recombination. This stage uses specific optical actuators as ODL for OPD control and T/T mirror for beam incidence correction. This loop does not act directly on the S/C dynamics.
A micro-vibration analysis tends to prove that contributions of internal disturbances at high frequencies are negligible on OPD for Emma. Only the control of disturbances due to the scan T/T mirror (to follow the array rotation while BCS keeps inertial attitude) is quite constraining and necessitates a few Hertz bandwidth.

Table 5.3-3 Third external control stage equipments

Fringe Sensor	Tilt accuracy requested: 20mas; OPD determination accuracy: 0.075nm
Corrective T/T mirror	Stroke < 300as; accuracy < 3mas
Optical Delay Line	Control accuracy < 1nm; stroke < 1cm

Figure 5.3-4 presents typical control loops performance in observation mode.

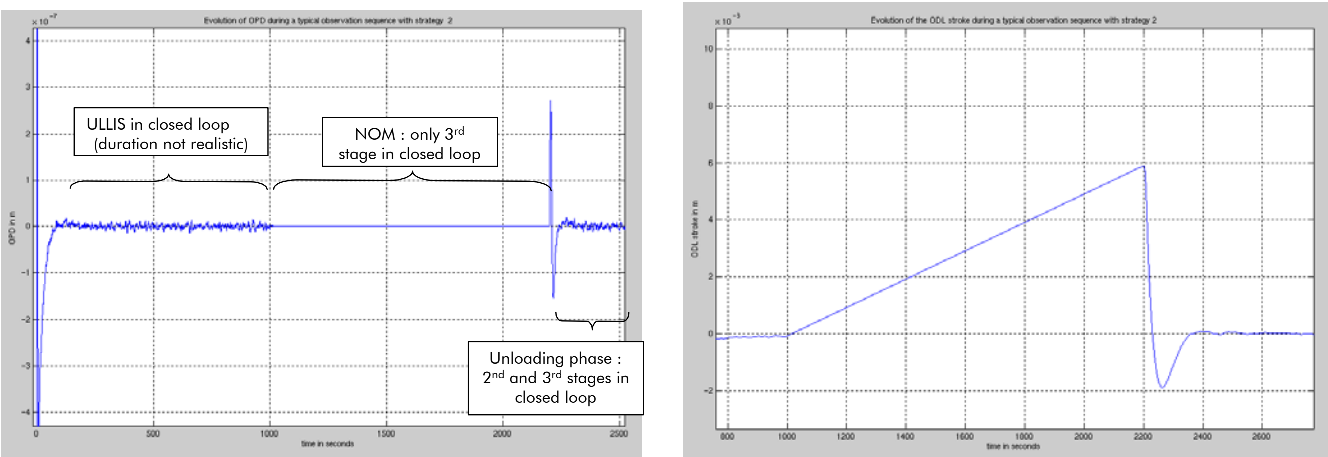


Figure 5.3-4 OPD & ODL stroke during typical observation sequence, strategy 2

5.3.2 Internal stage

Performance guaranteed at the third external control stage where the FS is located will be hardly kept passively up to recombination owing to unavoidable environmental perturbations (thermal effects, microvibrations). Indeed most of the large number of optical functions needed prior to the recombination (see Figure 5.2-1) must be located downstream the FS for operational wavelength reasons.

Internal control is thus required in order to compensate drifts and instabilities within the very stringent requirements. However internal metrology is in any way a refinement of the stage above, its performance requirements are the same as the third external control stage.

Concepts have been proposed, that can be easily accommodated in the beam combiner optical design. Sharing common optical paths with science beams, providing its own source, and operating at wavelengths as close as possible to science, are strong drivers.

5.4 Spacecraft description

5.4.1 Thermal control

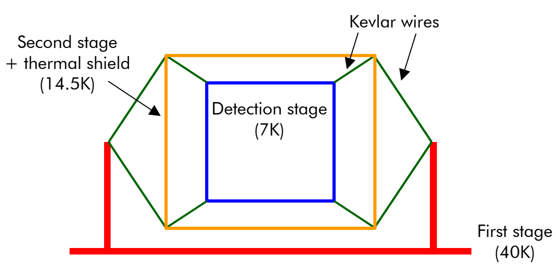
The proposed thermal architecture considers the thermal drivers summarised on Table 5.4-1.

Table 5.4-1 A thermal control design is proposed for each thermal function

Thermal function	Requirement	Baseline
BCS detectors cooling	Detector cooling between 8K and 11K	Ensured by the sorption cooler developed by University of Twente
BCA optical bench stability	OPD stability of 0.14nm rms (TBC)	Use of CeSiC material for optical benches Implementation of dissipating actuators (ODL) as far as possible from optical blades
Payload cooling	Operational temperature requirement of 40K for BCS and 45K for CS	Passive concept composed of: • a non-deployable sunshield • non-deployable V-Grooves system • passive radiator: composed of black painted honeycomb (similar to those used on the Planck payload) • low conductive struts: based on Planck PLM design
SVM temperature regulation	To maintain all SVM components at their operating temperature range	Regulation lines associated to radiators with black paint and OSR coating
Decontamination heaters	To prevent from any contamination of the optics (especially during launch)	Decontamination lines

Inside the BCA, the detector used is based on SiAs technology, cooled down to 8K. The need for thermal stability has been assessed at ±10mK for long term (2 weeks) at the operating temperature. Six linear 30-pixel detectors are foreseen on the focal plane: the total power consumption is estimated at 1mW.

The detection stage includes the focal plane and the sorption cooler cold end. The detection stage is supported by Kevlar wires to the second stage (see Figure 5.4-1). The 2nd stage is equipped with a thermal shield cooled at 14.5K by a H_2 sorption cooler. The 1st stage, supporting the 2nd stage, is mounted on the BCA bench by kinematic mounts.



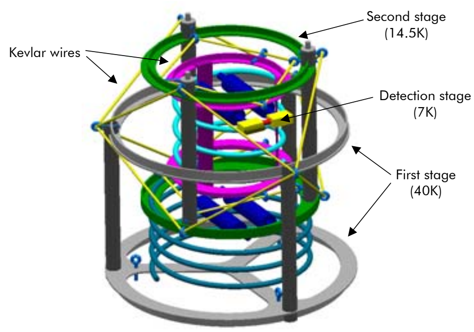


Figure 5.4-1 Cold stages thermal concept and assembly[8]

[8] University of Twente design

5.4.2 Mechanical and thermal architecture

The main architecture and design drivers are as follows:

- S/C design:
  - Satellites positioning and metrology, as well as optical path quality and stability require adapted structural concepts. In particular, these structures need to be adapted and master microvibrations and thermo elastic effects.
  - Mass and volume aspects in order to be able to launch Darwin to L2 with a single standard Ariane 5 ECA launcher, with the largest possible collectors aperture.

- Specific payload thermal and straylight constraints:
  - Use of thermal concepts and technologies to ensure the temperature regulation of the SVM around 290K and cryogenic payloads at 40K, concept being optimised to allow very stable condition on the critical elements (optical devices, optical benches, detection and all metrology systems).
  - Minimisation of thermal gradients during integration time require the bench holding the BS to have the highest as possible thermal conductivity at 40K.
  - Minimisation of thermo-elastic distortions need to be handled with adequate material selection (minimised thermal expansion at 40K) and isostatic constructions.
  - Alignment stability constraints to be met by technologies and material stability between ambient and 40K
  - The different payloads require the implementation of passive (to 40K) and active cooling systems to detection cold stage.
  - These payloads (BCS and CS) temperatures are not compatible with any factor of view to the Sun
  - A CS payload must have a very reduced FOV to other CS, and as well to BCS SVM warm parts.
  - External shapes and satellites architectures need to be adapted so the straylight from one S/C to the others is strictly minimised: no optical view of cold optics with any part of other satellites.

- Launch constraints: the Darwin system is to be launched on a single Ariane 5 ECA, with no propulsion module; the mass capacity of this launcher has been assessed by Arianespace to 6600kg to L2.

An overall view of the BCS, CS and launch configuration is illustrated on Figure 5.4-2.

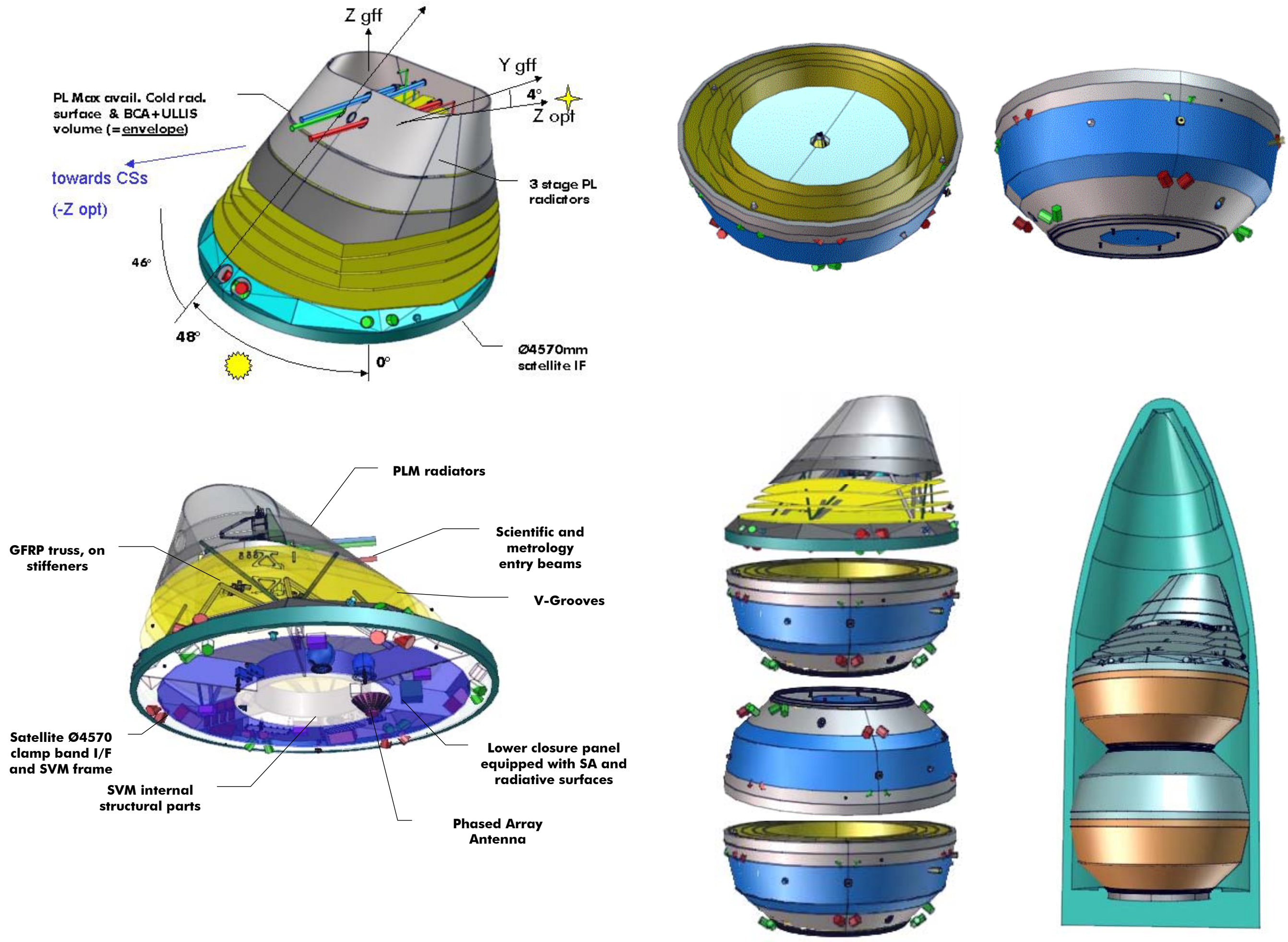


Figure 5.4-2 Overall view of the BCS (left), CS (upper right) and launch configuration (lower right)

Our proposed non deployable BCS and CS design is compatible with a 3 CS-arrangement, on a single ECA Ariane 5 medium fairing launch.

This design fulfils at the same time auto-stack-ability, very large mirrors working at cryogenic temperature with completely passive cooling systems, inter satellite metrology with no direct factor of view the 40K Payload and satellites warm parts, sufficient power, as well as satellite wide accommodation possibilities and flexibility.

The implementation of a 4^{th} collector S/C is also feasible with for instance a higher mass capacity to L2.

5.4.3 Command/Control

Avionics architecture:
BCS architecture is presented Figure 5.4-3. The formation level is centralised in the BCS, whereas other functions are common to all satellites. For GNC subsystem, only attitude loops are decentralised in operational phase. Position loops can be decentralised in a degraded mode.

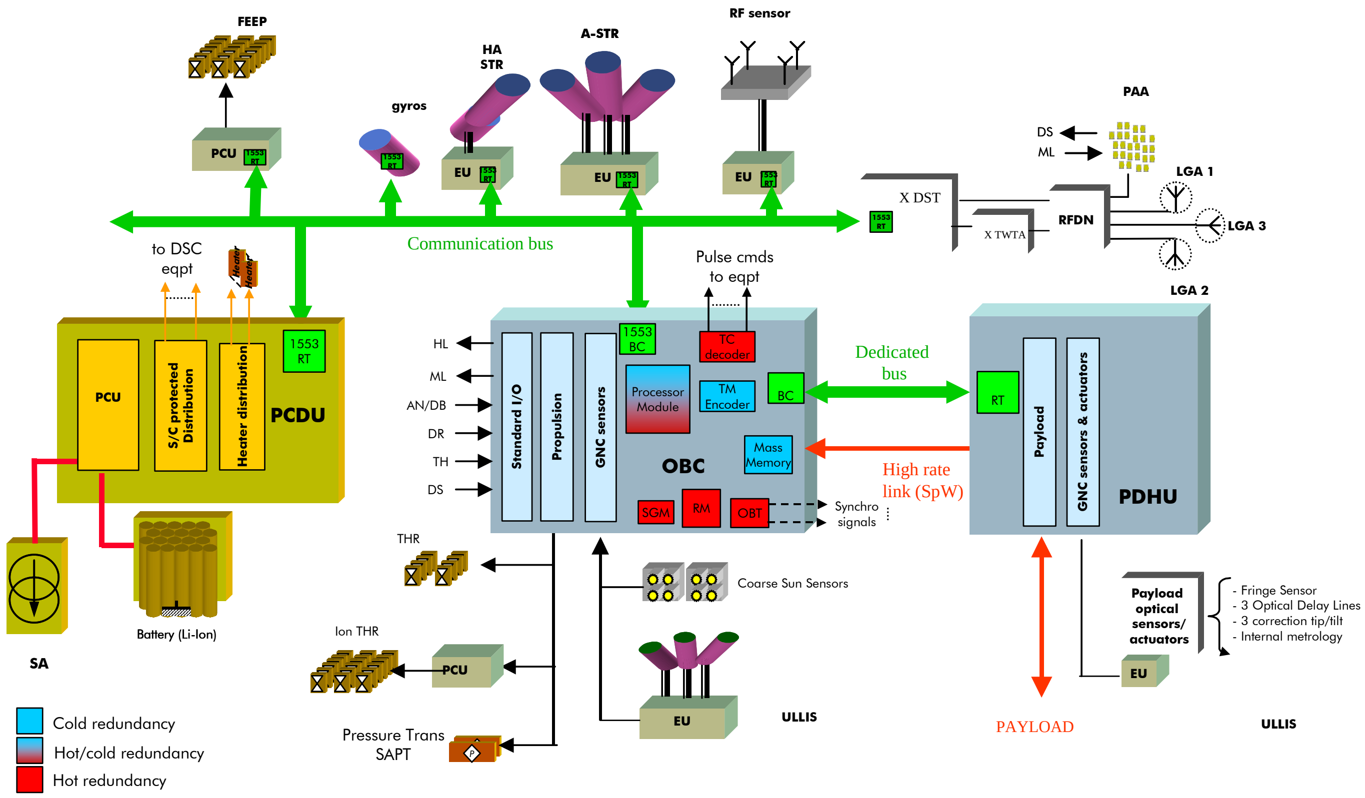


Figure 5.4-3 BCS avionics architecture

Telecommand Tracking Control architecture:
Science products are downloaded during Normal Operation Mode. The use of a Phase Array Antenna accommodated on BCS allows avoiding decreasing mission Duty Cycle (no attitude slew manoeuvres for antenna pointing are requested).

5.5 Orbit and deployment

5.5.1 Orbit analysis

Two types of operational orbits in L2 have been envisaged:

- Large Amplitude Lissajous orbit (LAL): quasi free ΔV transfer to L2 but larger Earth Aspect Angle (EAA) from BCS axes for Telecom with the Earth.
- Small Amplitude Lissajous orbit (SAL): requires large ΔV for transfer and eclipse avoidance manoeuvre but allow reduced EAA.

One of the major constraints taken into account was to comply with a single Ariane5-ECA launcher (mass limit of 6,600kg for overall S/C assembly), while excluding the use of a dedicated Propulsion Module.

The LAL orbit solution has been retained:

- A launch window available every day of the year allows to have always Sun S/C Earth (SSCE) angle < 35°, compliant with antenna technology and allowing important EAA for science product downloading without observation interruption.
- Orbit maintenance on operational orbit is realized by ion-THR.
- No eclipse avoidance manoeuvre is required on operational orbit.

<u>Launch window and additional ΔV</u>:
Figure 5.5-1 shows the launch opportunities to achieve LAL orbits. The inclined belts of no solution correspond to transfers affected by eclipses, which have been rejected. Colour graduation gives indication of the value of the maximum SSCE angle. Additional ΔV (w.r.t Ariane 5 transfer orbit) required to actually get captured in the L2 vicinity is small: within 10m/s.

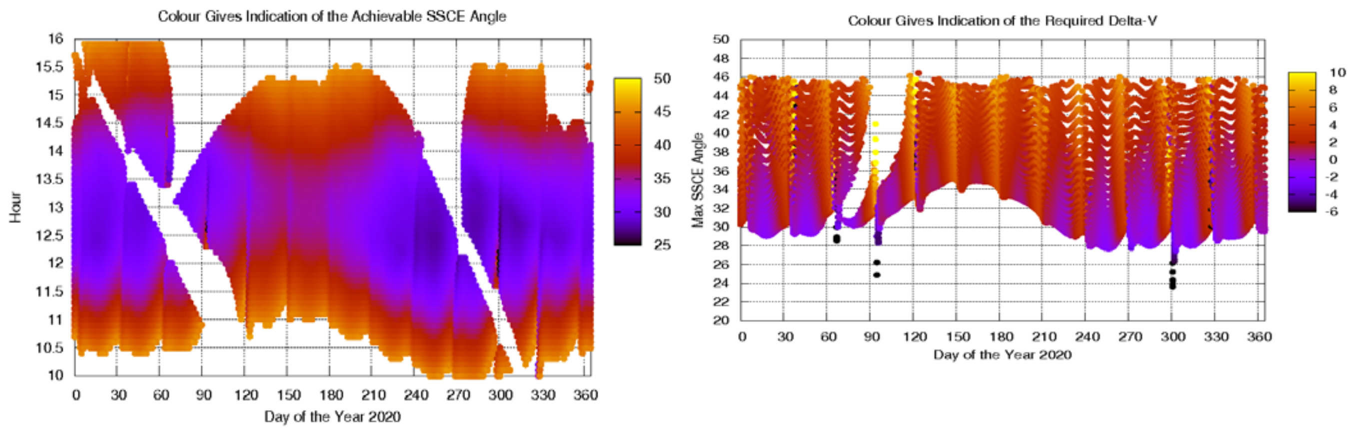


Figure 5.5-1 A launch window available every day with small required ΔV

Typical achievable LAL orbit:
Launching on January 19th at 12:30 achieves a SSCE angle of about 29.0°. a detailed view of the transfer and LAL with SSCE is provided on Figure 5.5-2.

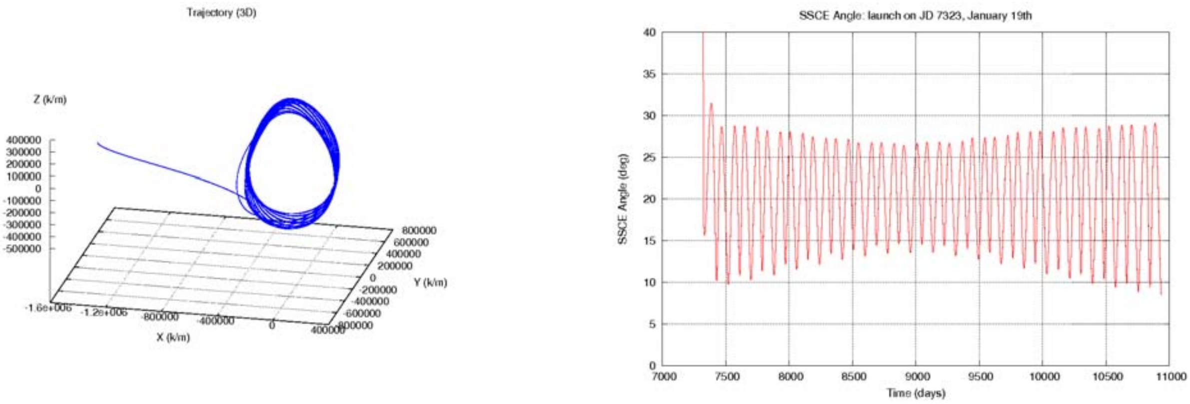


Figure 5.5-2 Free transfer to LAL & SSCE angle for typical LAL orbit

Preliminary budget for LAL:
According to our current baseline, which does not consider the exploitation of a dedicated propulsion module, Table 5.5-2 gives preliminary ΔV budgets. Thrust is realized using chemical propulsion.

Table 5.5-1 ΔV budget for transfer to L2

Removal of launcher dispersion	45m/s
Compensation of Perigee velocity variation	30m/s
Correction during transfer	4m/s to 15m/s
Total with system margin	**ΔV = 100m/s**

Comparison LAL/SAL orbits:
Table 5.5-2 shows comparative mass budget for two types of propulsion for transfer ΔV, applied to the both types of possible operational orbits.

Table 5.5-2 SAL are not achievable using chemical propulsion

Total mass (Kg)	Chemical	Electrical
Dry mass of the overall S/Cs assembly	6300 Kg	
Possible operational orbits:		
LAL	**6570**	**6300**
SAL (direct injection technique)	**7030**	**6320**
SAL (Amplitude Reduction technique)	**7080**	**6330**

Given that a single Ariane 5 launch to L2 has a mass limit of about 6,600kg, any chance to achieve a SAL operational orbit with chemical propulsion is unaffordable. LAL orbits present the unquestionable advantage of being cheaper from the fuel-consumption viewpoint.

SAL orbits are more suitable operational orbits from the scientific point of view. Problem with SAL is that they are extremely demanding from the point of view of fuel consumption. SAL orbits compatible with a single Ariane 5 launch are theoretically achievable only through electrical propulsion at the price of an increased operational complexity. The feasibility of electric propulsion to perform the insertion manoeuvre has been explored for the available ion-thrusters level. It was found that the thrust arc extended for more than 150 days and it would require delaying the beginning of the operational phase to accommodate the manoeuvres. Additionally, the inherent complexity of performing such a high manoeuvre in formation has to been taken into account.

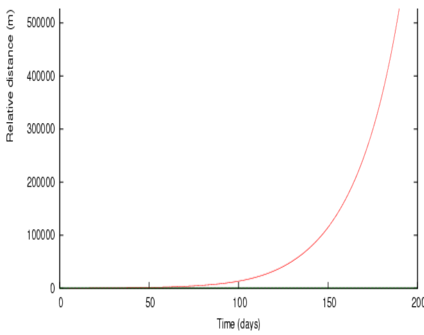
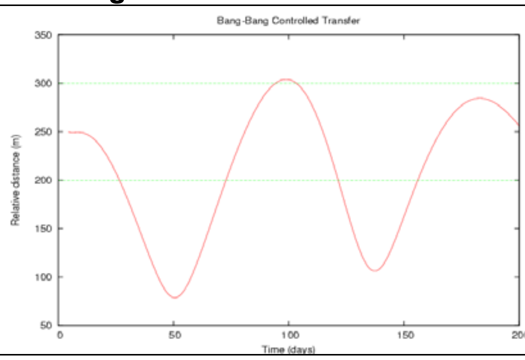
All the above considerations lead to discard a SAL orbit, orienting the effort to define a LAL mission, which fulfils the main operational constraints.

5.5.2 Deployment

The Darwin mission is conceived as a formation of four S/C around L2. According to the proposed mission baseline defined in previous chapter, the S/C should be deployed shortly after launch and before the correction manoeuvre to remove the launch dispersion.

The objective is to introduce a methodology to carry out transfers in loose formation with a geometry minimising the radial acceleration, and consequently minimising the ΔV required to maintain the flyers within admissible distances. Some preliminary explorations of free and controlled motions of two S/C moving along the transfer trajectory and using the Zero Relative Radial Acceleration (ZRRA) cones are shown on Table 5.5-3.

Table 5.5-3 Evolution of the inter S/C distance in free or controlled motion to L2

	Inter S/C distance: non-controlled	**Inter S/C distance: controlled on a generatrix of a ZRRA cone**
mutual distance between the two S/C versus time		
Max inter S/C distance	800km over 200 days	305m over 200 days. Required ΔV=2.8mm/s for maintenance.

5.6 Interface budgets

5.6.1 Mass and power budgets

Mass (kg) with 20% system margin	**BCS**	**CS**
Unitary mass	1663	1633
Total (1BCS + 3CS)	**6563**	

Power (W) with 20% system margin	**BCS**	**CS**
Unitary power	1339	641

5.6.2 Propellant budget

	BCS	**CS** (per S/C)
Hydrazine for transfer to L2	55kg	63kg
Electric milli-Newton for resizing, retargeting.	3.5kg	3.3kg
Electric micro-Newton for Observation	1kg	1kg

5.6.3 Data rate budget

ISL communication budget in operational mode	**BCS → 1 CS**	**1 CS → BCS**	**1 CS → 1 CS**	**BCS → Ground**
	Continuous per day			*Over 8 hours/day*
Science data (1)	0	0	0	2.7Mbps
GNC loop data (forces, sensor asurts)	0.2kbps	< 0.2kbps	0	28kbps
GNC HK data	0	1.8kbps	0	
Other HK data	0	5kbps	0	60kbps
FDIR supervision data	< 0.1kbps	< 0.1kbps	< 0.1kbps	
OBT synchronisation data	0	< 0.1kbps	< 0.1kbps	
TOTAL	**< 0.3kbps**	**< 7.2kbps**	**< 0.2kbps**	**2.8Mbps**

(1) Science products + 3rd external control stage data for ground processing is 900kbps (using 45Hz Fringe Sensor sampling rate).

6. SUMMARY AND CONCLUSIONS

Phase 1 trade-off and Phase 2 design activities clearly point out Emma as the right solution thanks to its higher useful mass (in terms of optical payload) as compared to Charles:

- Owing to system constraints imposed by the launcher, Emma is far superior to Charles in terms of detection and spectroscopy capabilities, and far superior to Charles in terms of accessible number of stars.
- The non deployable sunshield and V-Grooves on Emma translate into a much safer concept than Charles:
  - the absence of mechanisms grants an undisputedly higher reliability;
  - the absence of large flexible appendages avoid any spurious dynamical effects.

In addition, with the present system constraints, four large diameter (>2.2m) telescopes are not accommodable in one Ariane 5:

- This leads to select Emma Triangular Orthogonal Three-Telescope Nuller (TO-TTN) as the best compromise between science return maximisation and respect of system constraints.
- Some relaxation of those constraints could however make it possible to easily implement an Emma X-Array solution providing a mission performance equivalent to Emma TO-TTN with some potential although not determinant advantages as regards TO-TTN.

Some issues are still pending (most of them common to Charles and Emma):

- none of them would harm the demonstrated feasibility;
- their investigation will lead to a consolidate set of recommendations for technological developments;

the Darwin programmatics affords to smooth out those issues in time.

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