Project: DARWIN

System Assessment Study

Contract No.: 19333/05/NL/HB

Title: **Summary Report**

	Name	Date
Prepared by:	Oswald Wallner	12. Dec. 2006
Approved by:	Oswald Wallner Klaus Ergenzinger	12. Dec. 2006
Project Management:	Oswald Wallner	12. Dec. 2006

Distribution List

Quantity	Type	Name	Company/Department
1	PDF	P. Gondoin	ESA / ESTEC
1	PDF	O. Wallner	Astrium GmbH / AED41
1	PDF	K. Ergenzinger	
1	PDF	R. Flatscher	
1	PDF	U. Johann	
1	PDF	J. Borde	Astrium SAS / AEF41
1	PDF	R. Wall	Astrium Ltd / AEU41

Change Record

Issue	Date	Pages	Changes	Release
1	12.12.2006	All	Initial issue	1

Table of Contents

1 Mission and Study Objectives

The **DARWIN mission** aims at the search and the analysis of terrestrial exo-planets which orbit nearby stars at distances up to 25 parsecs. The major technical challenge is the huge contrast ratio and the small angular separation between star and planet. The observational method to be applied is nulling interferometry. It allows for extinguishing the star light by several orders of magnitude and, at the same time, for resolving the faint planet.

The first objective of DARWIN is to search for planets in the habitable zone of target stars. The target stars are main sequence stars of type F, G, K, or M with corresponding B-V colours, a luminosity class of IV-V or V, and visual magnitudes of less than 12. The second objective of DARWIN is a detailed analysis of the planets found. This includes the determination of the physical parameters as orbit, temperature, or evolutionary status and the analysis of the atmosphere by spectroscopy if an atmosphere is present. The third, ancillary objective of DARWIN is interferometric imaging.

By the analysis of biomarkers in the planet's atmosphere, DARWIN will be able to discern if the planet can carry life similar to that known on Earth and, if indicators for life are found, it will be able to determine the evolutionary status (Fig. 1-1 shows exemplarily the absorption spectra of Venus, Earth and Mars.). The DARWIN mission will therefore have a profound impact on mankind's understanding of itself.

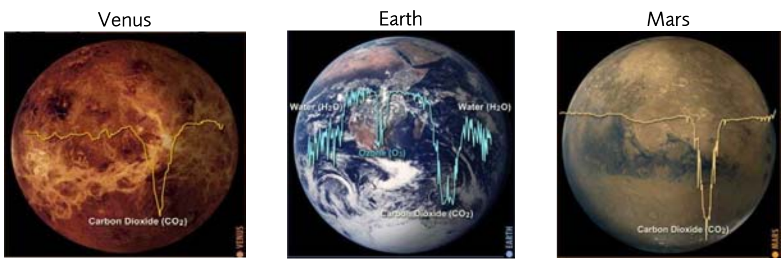

Fig. 1-1 Absorption spectra of the planets Venus, Earth and Mars (www.esa.int).

The objective of the **DARWIN System Assessment Study** is the definition of the overall architecture and the preliminary design of the DARWIN mission. This includes an operational orbit at the Second Lagrange Point of the Sun-Earth system (L2), a launch and transfer scenario, and a spacecraft and payload design which ensure that the mission requirements can be fulfilled. The specifications of the subsystems have to be derived, critical items and drivers have to be identified, and required technology development activities have to be proposed in order to allow for establishing a roadmap towards the verification of the science performance feasibility.

The DARWIN System Assessment Study is divided into two phases. Phase 1 is concerned with a review and trade-off of different concepts concerning the payload, the space segment, and the mission. Phase 2 is devoted to a detailed design of the payload and the space segment, as well with a consolidated mission design. A third phase is foreseen for design consolidation.

2 Industrial Study Team

Astrium, the leading European space mission company with long standing experience in science missions, has been or is currently involved in virtually all major ESA missions. A team of experts has been set up which provides optimum expertise and heritage in all fields relevant for the DARWIN mission in general and specifically for the DARWIN System Assessment Study.

Astrium GmbH (Friedrichshafen, Germany) is the prime contractor and responsible for the mission concepts, for the beam combiner spacecraft payload design, for system and science performance prediction, and for overall study management. Astrium GmbH has extensive experience in interferometric systems and hardware (e.g. DIVA, OISI, PRIMA, LISA) and mid-infrared instrumentation (e.g. MIPAS, NEARSPEC). Astrium GmbH has been or is currently involved in most of the DARWIN related activities as definition studies (DARWIN-GENIE), simulation (FINCH, BEAMWARRIOR), breadboards (MAII), optical metrology activities (HPOM, FFGTB, PROBA-3), or technology development activities (SMF, FOWF, ODL).

Astrium SAS (Toulouse, France) is subcontractor and responsible for the collector spacecraft payload design and for the formation control design. Astrium SAS has extensive expertise in the design and manufacturing of large space telescopes (e.g. Herschel, SPICA) and in formation flying and optical metrology (e.g. ICC, HPOM, PEGASE).

Astrium Ltd (Stevenage, UK) is subcontractor and responsible for the spacecraft design and for the mission aspects as operational orbit, launch system and transfer scenario. Astrium Ltd has extensive expertise in spacecraft design (e.g. LISA-Pathfinder) and in mission analysis from numerous science missions for ESA.

To complete the expertise, the Astrium study team is supported by consultancies from **TNO** (Delft, The Netherlands), **Sener** (Las Arenas, Spain), **MPIA** (Heidelberg, Germany), **ATC** (Edinburgh, UK), and from A. Léger from **IAS** (Paris, France).

3 DARWIN Mission

The DARWIN instrument is a space-borne nulling interferometer operating in the mid-infrared wavelength regime from 6.5 to 20 micrometers. The instrument is distributed over several spacecraft, one beam combiner spacecraft (BCS) and several collector spacecraft (CS), which fly in a closely-controlled formation.

The DARWIN instrument is to be launched from Kourou, French Guiana, by means of an Ariane 5 ECA launcher to its operational orbit at the second Lagrange point L2 of the Sun-Earth system, see Fig. 3-1

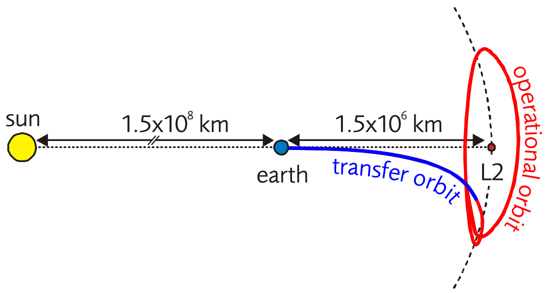

Fig. 3-1 Schematic of the transfer orbit and the operational orbit at the second Lagrange point L2 of the Sun-Earth system.

After formation deployment, highly accurate alignment of the individual spacecraft with respect to each other is performed by the high-precision optical metrology and the micro-propulsion system. The optical path lengths from the telescopes onboard the collector spacecraft up to the beam recombination unit onboard the beam combiner spacecraft are equalized and maintained by active control. In this way a spacecraft formation is established with a receive characteristic adapted to the target to be observed. The nominal position of the spacecraft relative to each other is established and maintained by a formation control system so that the interferometer can be formed by its distributed optical components.

The signals received by the telescopes on the collector spacecraft are relayed to the beam combiner spacecraft where proper modulation methods (phase chopping, array rotation) are applied in order to increase the instrument's sensitivity and where the signals are superimposed by a beam recombination scheme in order to extract the planetary signal.

The DARWIN interferometer, after deployment and in science operation formation flying, is comprised of a distributed payload residing on the beam combiner spacecraft and the collector spacecraft, see Fig. 3-2. The orientation of the payload and the internal interconnection is established and maintained via formation control and active optical elements acting essentially as a virtual truss and as a precision pointing sub-system. The formation control functionality is based on hardware distributed among the payload assemblies of all spacecraft and partially residing in the service modules.

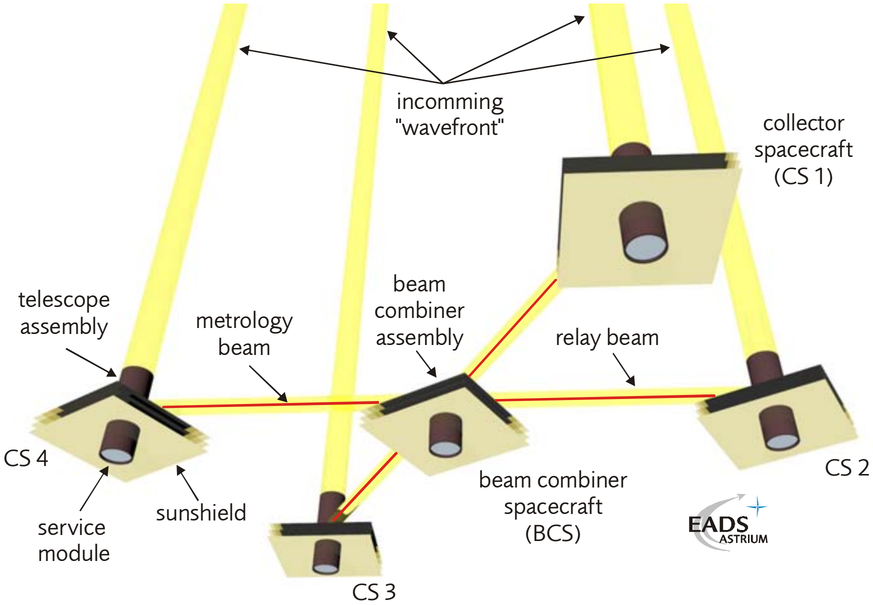

Fig. 3-2 The DARWIN interferometer configuration, showing the distributed payload on the collector spacecraft (CS) and the beam combiner spacecraft (BCS) in science mode formation flying.

4 Instrument Concept Trade-Off

To arrive at the optimum design for the DARWIN mission which allows for maximum scientific return, we have evaluated and traded the most important mission options and alternatives. These are:

- Aperture configurations with three or four telescopes, see Fig. 4-1.
- Planar or non-planar spacecraft formation.
- Interferometer implementation concerning modulation by phase chopping array rotation and beam recombination with co-axial (pupil-plane) or multi-axial (image plane) schemes.
- Operational orbit at the second Lagrange point L2 of the Sun-Earth system.
- Launch and transfer scenario concerning launcher, direct injection or launch to an intermediate orbit, and transfer propulsion.

Based on this trade-off and based on the achievable science performance, we propose a planar x-Array spacecraft formation employing pupil-plane (co-axial) beam recombination, directly injected by a single Ariane 5 ECA launcher into a transfer to a Halo orbit at L2. The launch composite stack is separated early in LEOP and a chemical propulsion system is used for correction manoeuvres.

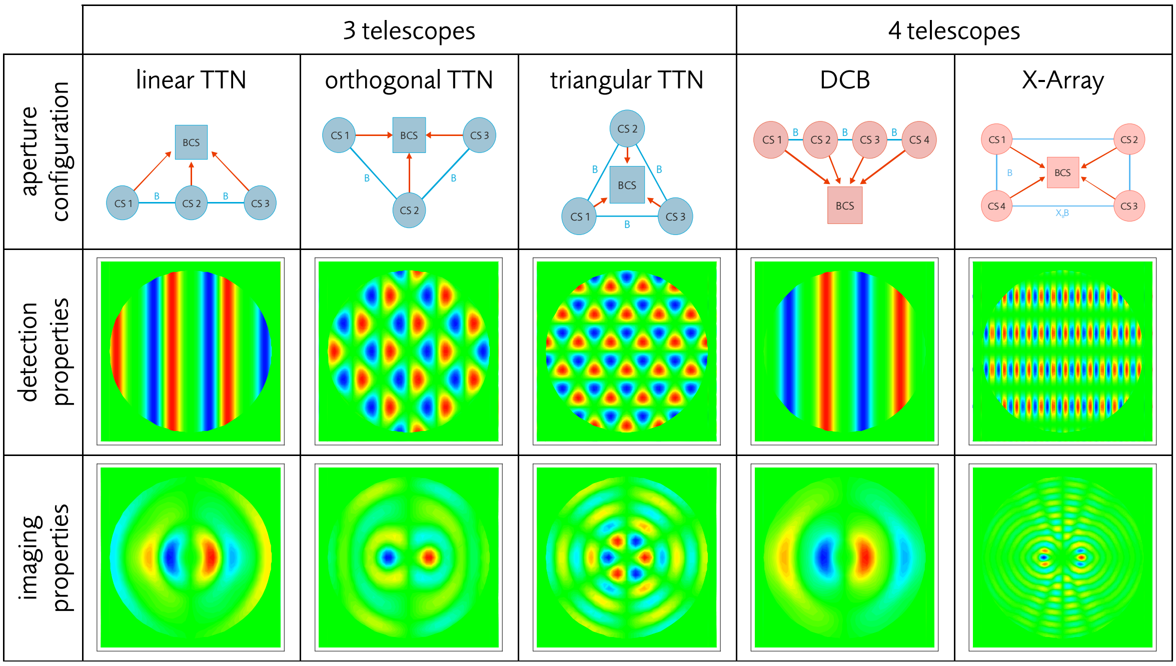

Fig. 4-1 Detection and imaging properties of three and four telescope configurations. The first row shows the aperture configuration, the second row the receive characteristic of the instrument after applying phase chopping and the third row the correlation map for image reconstruction.

The proposed instrument implementation is perfectly symmetric w.r.t. optical path length, transmission and state of polarization, most efficient due to the co-axial recombination scheme implementation and the larger collecting area, and least sensitive to perturbations by applying co-axial (pupil plane) beam recombination. The major advantages of the proposed instrument implementation are:

- The x-Array offers a 33 % larger collecting area compared to TTN configurations.
- Because the beam recombination scheme is realized by two-telescope nullers, the x-Array allows for 100 % modulation efficiency compared 70 % achievable for TTN configurations.
- For the x-Array the achromatic phase shifter required for nulling is realized by a perfectly achromatic periscope instead of a dielectric achromatic phase shifter as required for the TTN. The latter represents a complex cryogenic mechanism with separate metrology.
- The x-Array allows for a simple single-material design of the $\pi/2$ phase shifter required for phase chopping because only the already nulled signals are recombined.
- The x-Array allows for science operation without reconfiguration even if one collector spacecraft completely fails and thus dramatically reduces the risk of mission loss.
- For the co-axial beam recombination scheme the requirements on alignment are by about one order of magnitude relaxed compared to multi-axial beam recombination.
- In a co-axial beam recombination scheme only the stellar leakage has to be radiated off by the single-mode fiber acting as modal wavefront filter. In a multi-axial scheme the entire star light has to be radiated off through the fiber cladding which imposes extreme requirements on the material homogeneity and stray light suppression.
- A co-axial beam recombination scheme for four beams allows for much higher throughput of 72 % compared to a multi-axial scheme for three beams which achieves only 43 %.
- A planar spacecraft formation has the advantage that the beam routing can be made perfectly symmetric w.r.t. polarisation. The beam routing of a non-planar configuration is inherently asymmetric and therefore leads to a degraded nulling performance.
- The instrument concepts for planar formations are well established compared to that for non-planar concepts. For the latter a complicated mechanism is required for beam de-rotation and baseline resizing. Further, the on-ground qualification of the collector mirror with 1 km focal length is regarded as very critical.
- Compared to TTN configurations, the planar x-Array allows for analyzing about twice the number of planets. It shows much higher angular resolution and therefore allows for detecting and resolving multi-planet systems.

The planar x-Array clearly outperforms all planar and non-planar three telescope (TTN) configurations in terms of scientific performance, technological risk and reliability at only marginally increased costs. The first glance advantages of three telescope configurations (TTN) are negligible compared to the severe drawbacks concerning instrument complexity and feasibility and achievable scientific performance.

5 DARWIN Science Objectives

The DARWIN mission aims at the search and the analysis of terrestrial exo-planets which orbit nearby stars at distances up to 25 parsecs. The first objective of DARWIN is to search for planets in the habitable zone of the target stars, the second objective is a detailed analysis of the planets found. Within the nominal screening phase of 2 years at least 225 targets shall be analyzed for the presence of a planet when assuming an exo-zodiacal dust cloud similar to that of our solar system and 150 targets for a ten times denser dust cloud. During the nominal spectroscopy phase of 3 years in total at least 22 or 15 targets shall be analyzed for 1 or 10 zodi dust clouds.

DARWIN operates in the mid-infrared wavelength regime. Compared to the visible, the mid-infrared has the advantage of contrast ratio between star and planet which is smaller by more than a factor of 1000, see Fig. 5-1. The observational wavelength range from 6.5 to 20 μm is determined by the atmospheric absorption features to be analyzed.

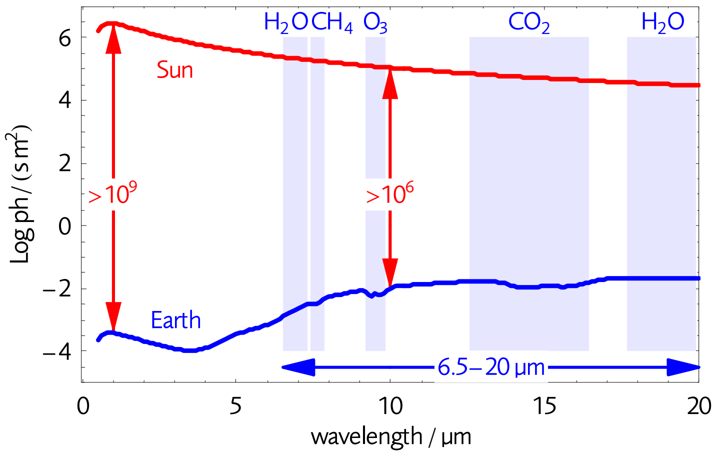

Fig. 5-1 Observational wavelength range and atmospheric absorption features for the DARWIN mission.

The target stars are main sequence stars of type F, G, K, or M with corresponding B-V colours, a luminosity class of IV-V or V, visual magnitudes of less than 12, and distances up to 25 pc. For planar formations the ecliptic latitude is limited to ± 45°. Stars of type G are most interesting for DARWIN as thy show the best similarity to the Sun. Thus 50% of the overall observing time is allocated to G stars, 10% to F stars, 30% to K stars and 10% to M stars.

The planets are located within the habitable zones around the parent stars, see Fig. 5-2. The habitable zone ranges from 70 to 150% of the habitable distance which amounts to 1 astronomical unit (au) for the Sun and scales with the luminosity of the star relative to the Sun luminosity. The apparent distance of a planet from the parent star follows a probability distribution. For each target, the planet is observed for a range of possible apparent distances to allow for a detection probability of 90%. In the planet detection phase the presence of a planet is proved and, in case, the physical parameters as orbit and temperature are determined. For detection a signal to noise ratio (SNR) of 5 is required. For parameter determination each target with a planet is visited three times.

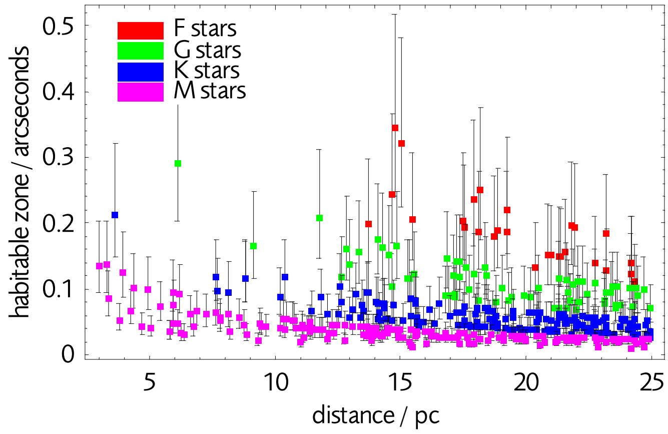

Fig. 5-2 DARWIN target stars with associated habitable zones.

By the analysis of biomarkers in the planet's atmosphere, DARWIN is able to discern if the planet can carry life similar to that known on Earth and, if indicators for life are found, it will be able to determine the evolutionary status. The planetary absorption features to be analyzed are the biomarkers water (H_2O), ozone (O_3) and carbon-dioxide (CO_2).

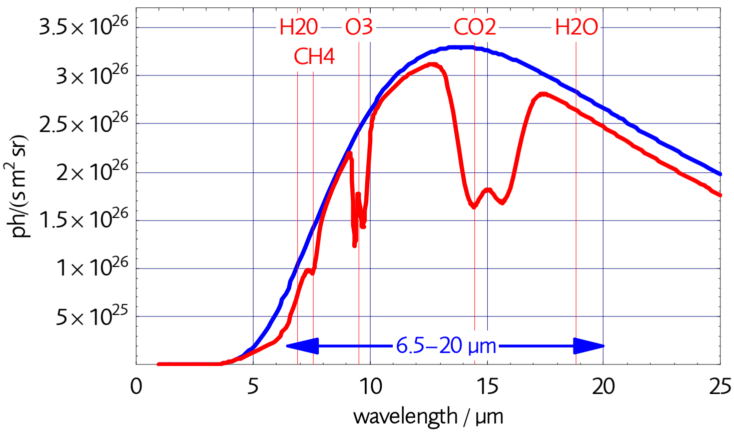

Fig. 5-3 Spectrum of an Earth-like planet without (blue) and with (red) the indicated atmospheric absorption features.

6 Preliminary Design of the DARWIN Mission

The DARWIN mission is to be launched by Ariane 5 ECA to an orbit at the second Lagrange point L2 of the Sun-Earth system. The proposed operational orbit is a free injection Halo orbit as it has advantages from a ΔV accessibility point of view as well as of a repeating geometry and of not featuring any eclipses.

Because the performance of Ariane 5 ECA strongly depends on the inclination of the transfer orbit, we have designed the launch and transfer scenario for maximum launch mass capability. A direct injection launch scenario is considered for DARWIN as it gives significant advantage in terms of mission complexity if compared to the option where the launch happens into an intermediate high elliptical orbit with subsequent apogee raising. The required launcher dispersion correction and range keeping manoeuvres are performed by chemical propulsion. A rough timeline for the DARWIN mission is given in Fig. 6-1.

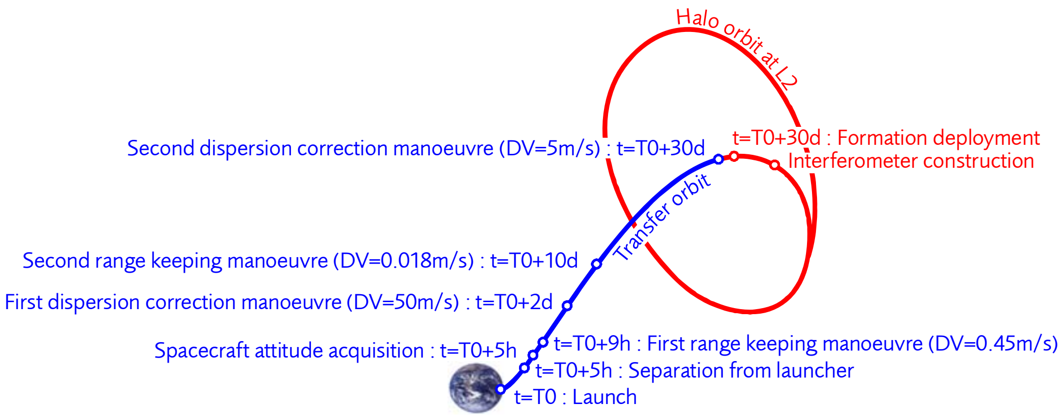

Fig. 6-1 DARWIN mission timeline.

The formation control system design is based on rms-value specifications which are derived from the requirements on the mean null depth. The design is compatible with the mission requirements, see Tab. 6-1.

Control loop	Performance rms
relative position	0.3 mm
BCS and CS attitude	1 as
Fine pointing (200 mm)	70 mas
OPD control	1 nm

Tab. 6-1 Formation control loop performance.

The DARWIN instrument consists of two types of spacecraft, the collector spacecraft and the beam combiner spacecraft. To limit the development costs, the four collector spacecraft are designed to be identical. For the service module of all spacecraft a design is chosen which allows for utmost equality. The payload design is driven by the requirement of highest stability and utmost symmetry between the beams to be recombined.

For the collector telescope a Gregorian design with a primary mirror diameter of 3.5 m has been assumed. To allow for compact stowing, a deployment mechanism is foreseen for the secondary mirror assembly support arm. The deployment arm is folded around the telescope during launch to allow for stacking of the spacecraft on top of each other in order. The secondary mirror assembly is aligned after deployment by aid of an alignment mechanism and of laser metrology.

The interferometer core of the x-Array aperture configuration is realized as a pair of two-telescope (Bracewell) nullers which are recombined with a relative phase difference of $\pi/2$. In this way the nulling and imaging properties of the x-Array are completely decoupled. For nulling the short baseline of the Bracwell nullers is relevant, while for imaging the long baseline between the two nullers is significant. We have selected an imaging to nulling baseline ratio of 3:1 as this allows for a good compromise between optimum scientific performance and instrument design constraints. The major advantages of the x-Array are that only two-beam recombination stages are required which allow for a recombination efficiency of 100% and that the high-accuracy nulling phase shifter is realized by a perfectly achromatic periscope instead of a dielectric achromatic phase shifter, which appears hardly feasible for the DARWIN spectral range.

The payload of the beam combiner spacecraft is designed for lowest complexity and highest symmetry. The structural design minimises the degradation of the optical performance due to gravity release and due to cool-down from ambient temperature to 40 K. The optical assembly of the BCS payload comprises 3 optical sub-assemblies (Fig. 6-2), the receive optical assembly, the nulling optical assembly and the detection optical assembly.

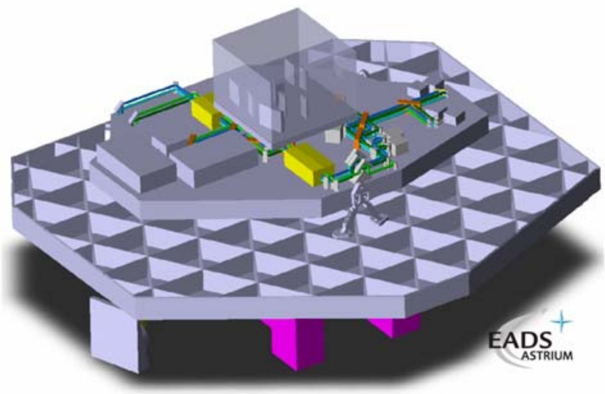

Fig. 6-2 Optical assembly of the BCS payload consisting of the receive optical assembly (at bottom level), the nulling optical assembly (at intermediate level) and the detection optical assembly (at top level).

The overall mechanical configuration of the beam combiner spacecraft and of the collector spacecraft in stowed and deployed configuration are given in Fig. 6-3 and Fig. 6-4.

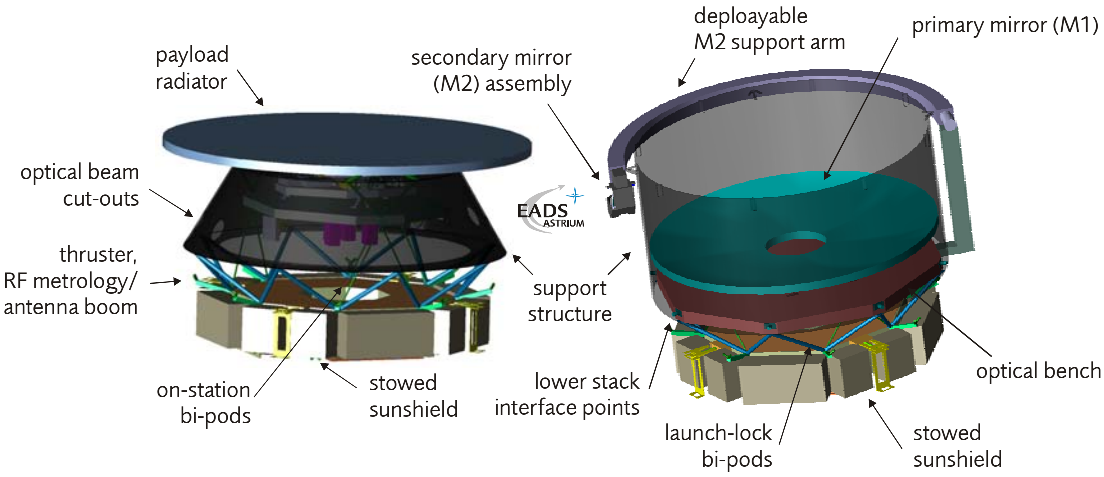

Fig. 6-3 Beam combiner spacecraft (left) and collector spacecraft (right) in stowed configuration.

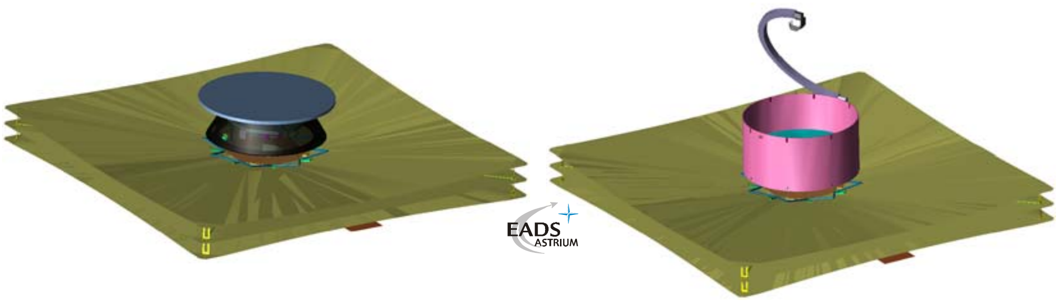

Fig. 6-4 Beam combiner spacecraft (left) and collector spacecraft (right) in deployed configuration.

The beam combiner spacecraft is mounted on top of the spacecraft stack with the 4 collector spacecraft stacked below. A special-purpose adaptor provides the interface to the 2624 mm diameter ACU mounting plane of the Ariane 5 ECA launch vehicle, see Fig. 6-5.

Each collector spacecraft incorporates a 3600 mm diameter cylinder that provides a primary load path from the top to the bottom of the stack outside of the diameter of the collector telescope main mirror. To allow for identical CS, the stacking cylinders are identical and dimensioned for the bottom spacecraft. To limit the overall height of the launch stack, the height of each cylinder is sufficient to permit the service module in its stowed configuration to be nested inside. The beam combiner spacecraft is mounted at the top of the stack via a support cone. The lower diameter of the cone provides the interface to the uppermost CS. The height of the cone is driven by the need for the optical beams from the CS to clear the edge of the deployed sunshield.

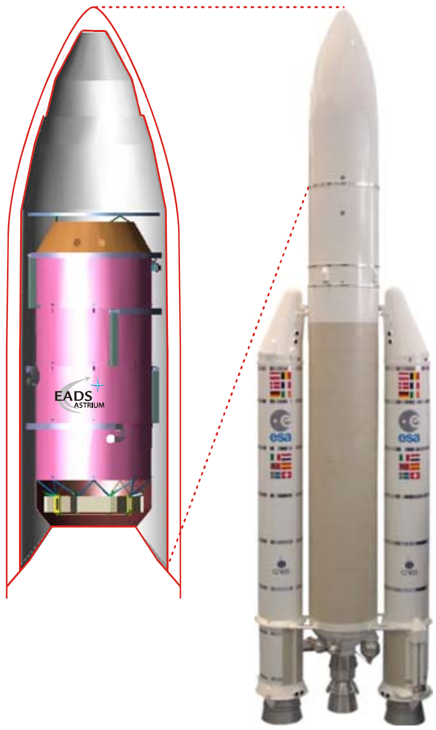

Fig. 6-5 DARWIN spacecraft stack, consisting of 4 collector spacecraft and 1 beam combiner spacecraft, accommodated within the Ariane 5 ECA launcher fairing.

7 Scientific Performance

Science performance simulations with the in-house developed interferometer simulator ISim showed that the DARWIN science requirements can easily be fulfilled and that the proposed instrument outperforms planar or non-planar three-telescope configurations (TTN) by a factor of about 2 in terms of the number of planets analyzed by spectroscopy.

A planar x-Array with an imaging to nulling baseline ratio of 3:1, a co-axial (pupil plane) beam recombination scheme, and a perfectly symmetric instrument implementation allows for screening of 446 targets of the target catalogue and for analyzing of 62 targets by spectroscopy within the nominal mission time of 2 years and of 105 targets during the extended mission time of 10 years, see Tab. 7-1.

exo-zodi level		1	10
detection (2 years)	total	446	446
detection (2 years)	F	29	29
	G	69	69
	K	163	163
	M	185	185
	total	446	446
spectroscopy (3 years) nominal mission	F	2	1
	G	15	5
	K	16	8
	M	29	11
	total	62	25
spectroscopy (3+5 years) extended mission	F	4	3
	G	26	5
	K	31	13
	M	44	19
	total	105	40

Tab. 7-1 Scientific performance of the planar x-Array (X_B=3) in terms of the number of targets screened during the detection phase (2 years) and the number of targets analyzed with rotating spectroscopy during the nominal (3 years) and the extended (8 years) spectroscopy phase.

8 Conclusion

A sound trade-off between different instrument and formation concepts has been performed for the DARWIN mission. We analyzed in detail different three and four telescope configurations, planar and non-planar spacecraft formations, different instrument implementations including co-axial and multi-axial beam recombination schemes and various launch, transfer and orbit options.

An optimum design for the DARWIN mission has been elaborated, including a planar x-Array spacecraft formation (see Fig. 8-1) employing pupil-plane (co-axial) beam recombination, directly injected by a single Ariane 5 ECA launcher into a transfer to a Halo orbit at L2. The launch composite stack is separated early in LEOP and dispersion correction and range keeping manoeuvres are applied by a chemical propulsion system.

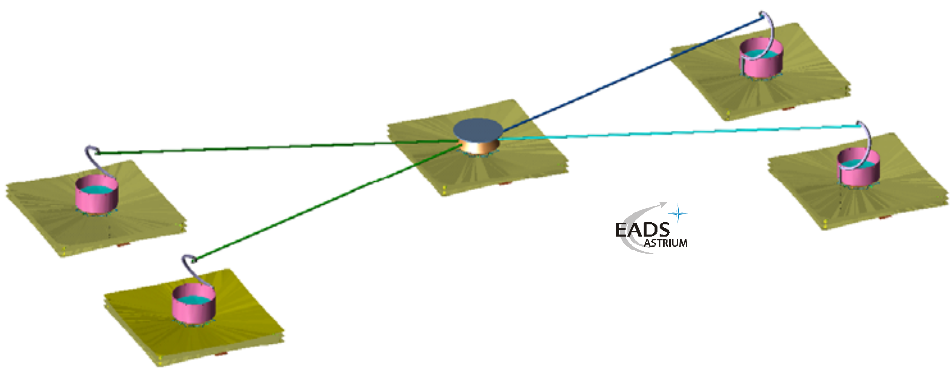

Fig. 8-1 Planar x-Array spacecraft formation with 3:1 imaging to nulling baseline ratio, showing the beam combiner spacecraft at center, the four collector spacecraft at the corners of a rectangle, and the relay beams.

The proposed planar x-Array clearly outperforms all planar and non-planar TTN configurations in terms of scientific return, technological risk and reliability at only marginally increased costs.

We have demonstrated that the DARWIN mission is feasible and that the scientific requirements can be best fulfilled with an optimized planar x-Array spacecraft formation and an optimized instrument implementation.