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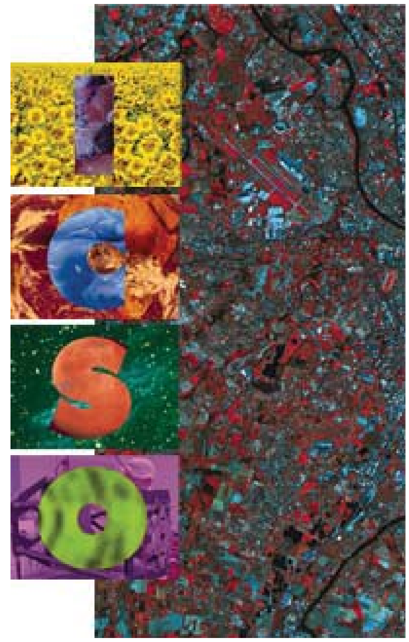

Darwin : the technical challenges of an optical nulling interferometer in space

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DARWIN : THE TECHNICAL CHALLENGES OF AN OPTICAL NULLING INTERFEROMETER IN SPACE

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ABSTRACT *- Alcatel Space has been responsible for a feasibility study contract, awarded by the European Space Agency, and dedicated to the definition of preliminary interferometric concepts for the direct detection and characterisation of exo-planets associated with nearby stars.*

The retained concept is a six free-flyer-telescope interferometer, with a variable baseline ranging from 50 to 500 m. The collected wavefronts are combined on a 7th free-flying hub satellite at the centre of the array, and the observations are performed in the thermal Infra-Red spectral band. The latter choice is made for two reasons : firstly, the wavelength providing optimal contrast between the planetary and stellar (background) signals is approximately 10 µm; secondly, the spectral features of interest for the detection of life as we know it (CO_2, H_2O, O_3 , CH_4 ...) lie in the band between 6 and 18 µm.

The system requirements for such an instrument are very severe, owing to the physical nature of the mission concept; i.e. that of a coronographic stellar interferometer: in order to achieve satisfactory extinction of the unwanted flux generated by the central star, such a concept will impose the control of optical pathlength differences between telescopes to within a small fraction of a wavelength, milli-arcsec pointing stabilities, 10^{-3} amplitude equalisation, achromatic π-shifts of some beams with respect to the others, and the use of passively cooled cryogenic telescopes.

1 MISSION AND PRINCIPLE

The ESA Science Programme is preparing a challenging future mission, DARWIN, whose principle objective will be to detect "Earth-like" planets outside our own solar system, and to determine whether any form of life exists on them. Since the star around which the planet orbits is dramatically more luminous than the planet, it has been proposed to implement a technique known as optical nulling, in order to reduce the observed luminosity of the star. This technique is designed to enable "direct" detection of the planetary photons, as opposed to indirect detection, such as reflex (radial velocity) and photometric occultation techniques. To achieve the desired spatial resolution, a very large aperture - which would be impractical to build it as a single element - is needed. The optical system is therefore based on the use of several distinct apertures separated by a variable distance, i.e. a large baseline interferometer.

Both planet detection and spectroscopy are performed by optical nulling, i.e. the nulled object is aligned with the optical axis of the different apertures. Before being interferometrically combined, some of the telescope beams are achromatically phase shifted, such that destructive interference is obtained for the on-axis star. With the bright star "removed", it is possible to observe less luminous objects near to the star, such as planets or proto-planetary disks.

A key aspect of the interferometer design is the control of the Optical Path Differences (OPD) to a small fraction of the wavelength of interest. Since the required baselines of the interferometer can extend up to 500 m, a free-flyer configuration is required. Single aperture telescopes are mounted on separated spacecraft flying in formation. The relative positions of the spacecraft must be controlled so that the OPD errors remain typically within a few nano-meters. In order to ensure minimal thermal, drag and gravitational disturbances to the free-flyer formation an orbital position at the 2nd Lagrange point (L2) has been selected

2 THE CONCEPT

The baseline system design is a free flyer configuration, known as the Laurance (or 3-GAC) space interferometer. It has six telescope spacecraft, flying in one plane in a hexagonal shape. A seventh spacecraft, the beam-combiner or hub spacecraft, receives the beams from the telescopes and performs the nulling interferometry. The Laurance interferometer is an overlay of three interferometers, rotated by 60 deg. The beam-combiner is flown in the centre of the hexagon and is also in charge of the overall formation control and ground communications.

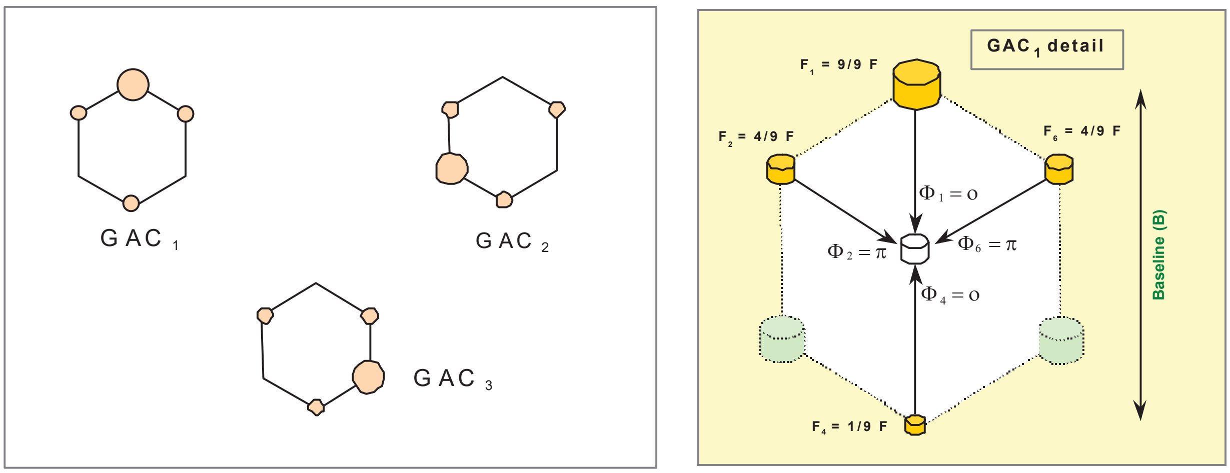

Figure 1 The Laurance nulling space interferometer consists of 6 equal size telescopes flying in a hexagonal formation, with the beam-combiner in the centre.

Three Generalised Angel Crosses (GAC) are overlayed in order to achieve internal modulation. As shown in Figure 1, the relative flux contributions from each of the telescopes in a given GAC are 9/9, 4/9, 4/9 and 1/9. By overlaying three identical GACs (left hand part of the figure), the total flux requirement for the 3 GACs can be provided by 6 identical telescopes.

The distances between the spacecraft are measured by three different methods:

- A generalised microwave ranging system, equivalent to a local GPS system, provides centimetric range accuracies. This system is used to determine relative positions of the spacecraft during formation deployment, baseline reconfiguration and emergency recovery situations.
- A laser ranging system, which can only be used once the spacecraft have been aligned in position and attitude to within ~ 1cm of their nominal array locations.
- Science object fringe tracking, uses the light collected by the telescopes to measure the optical path differences between the 6 arms of the interferometer.

The control of terminal & hub attitudes and relative motions is achieved using FEEP (Field Effect Electrical Propulsion) thrusters. All spacecraft carry individual startrackers. An artist's impression of the overall constellation is shown in the following figure.

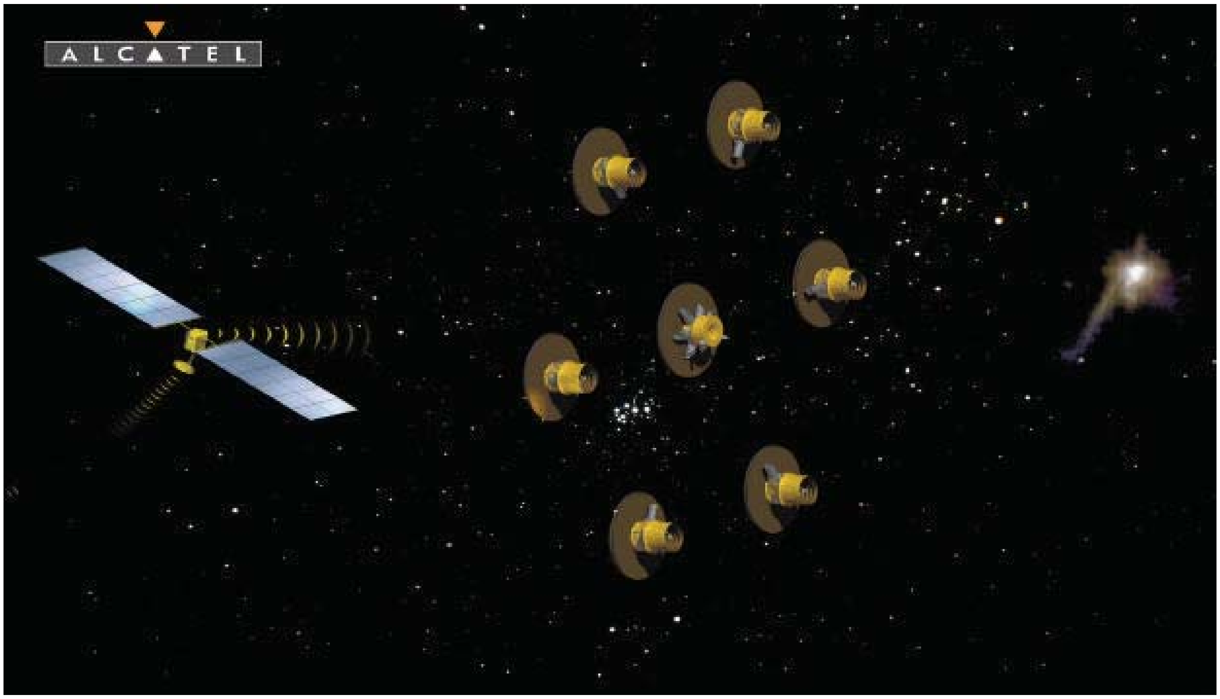

Figure 2 Artist's impression of the Robin Laurence interferometer

3 THE TELESCOPE COLLECTOR ARCHITECTURE

3.1 Optical concept

The minimum size for the main telescope pupils has been set to 1.5 m, which has been shown to be compatible with a 6-telescope interferometer configuration and Ariane 5 fairing accommodation requirements. As straylight shielding (from nearby stars) is very important for a nulling interferometer, the preferred optical design for the science telescope is that of a Korsch system with a parabolic primary and a field stop in the intermediate focal plane. The following figure shows the proposed design with its main functions.

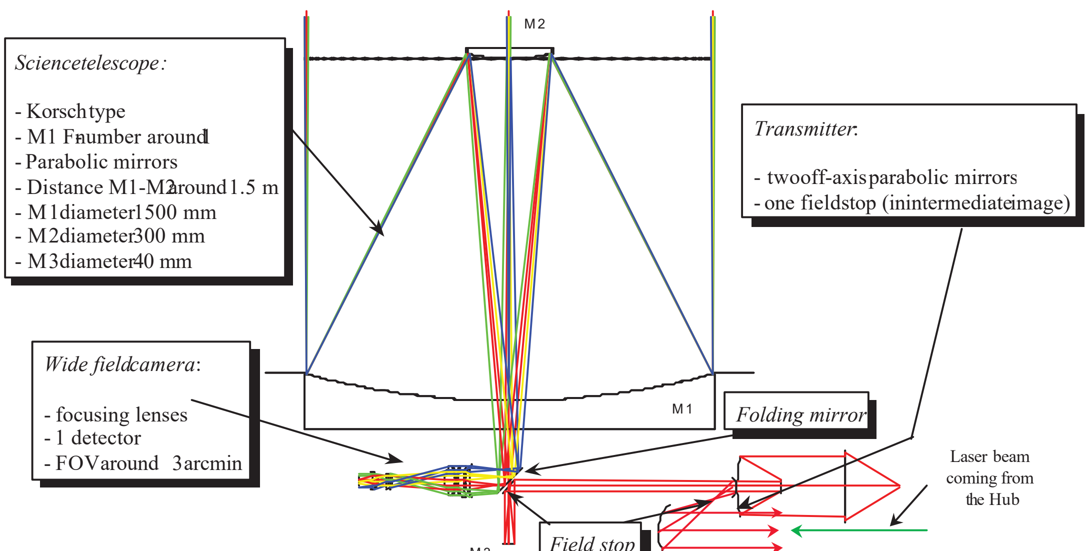

Figure 3 Telescope collector optical concept

The integrated wide field camera (WFC) shown in **Figure 3** acts as a fine pointing sensor, allowing the telescope to achieve very accurate and stable attitude control, using the flyer's fine AOCS system as a corrective actuator. The possibility of actuating the secondary mirror is considered only as a backup solution, to be envisaged in the case of excessive noise generated by the FEEP thrusters used by the pointing control system.

As shown in previous figure, a small field-separator (folding mirror with a central hole) is placed in the intermediate image plane. It has 2 functions : rays from objects in the outer part of the FOV are *reflected* towards the WFC to provide fine attitude sensing, whereas those from the central zone of the FOV (corresponding to the science target, as well as reference star – in imaging mode) are *transmitted* through the hole to the third mirror and then out to the hub combiner optics.

3.2 Thermo-mechanical concept

To ensure a high degree of alignment stability, a thick, rigid, and stable base-plate is used, to provide support for all of the optical elements. The main telescope structure, which is used to support the secondary mirror, is directly interfaced with the base-plate. This main telescope structure is basically comprised of a structural cylinder, which naturally fulfils the required optical and thermal baffling functions, and a secondary mirror spider.

In order to minimise telescope self emission, its temperature has to be cooled down to 40 K. A secondary structure (truss + base-plate) supports a sun- shield which is composed of three separate screens, which are deployable structures using folding arms and MLI foil. This concept is designed to minimise the effects of *radiative* coupling between the outer screen and the telescope optics. The V-grooves created between the screens enable most of the incident solar flux to be re-radiated to outer space.

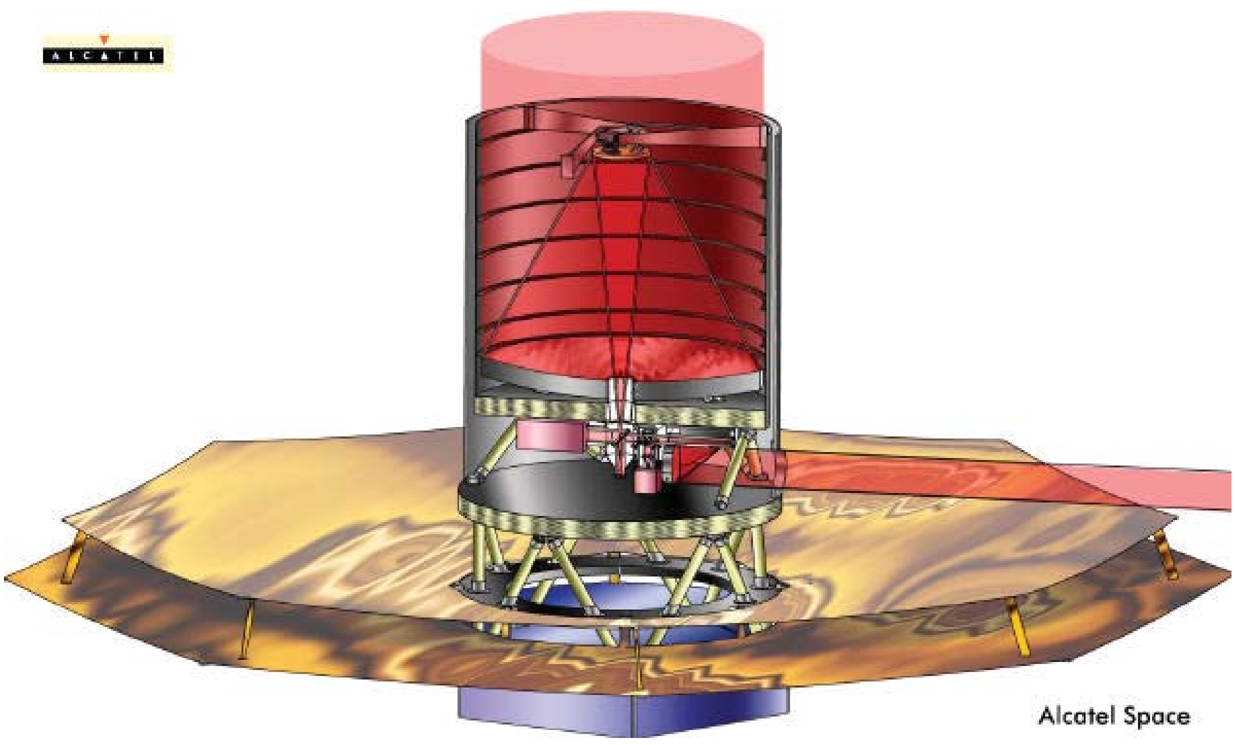

Figure 4 Telescope thermo-mecanical concept

4 THE BEAM COMBINER DESIGN

4.1 Optical principle

A whole class of so-called GAC (Generalised Angel's Cross) nulling interferometers has been proposed by A. Karlsson, B. Mennesson, et. al. These present the interesting advantage of an internal modulation capability, together with achromatic phase shift requirements of exactly π. The following figure illustrates the principles of this unusual beam combination scheme.

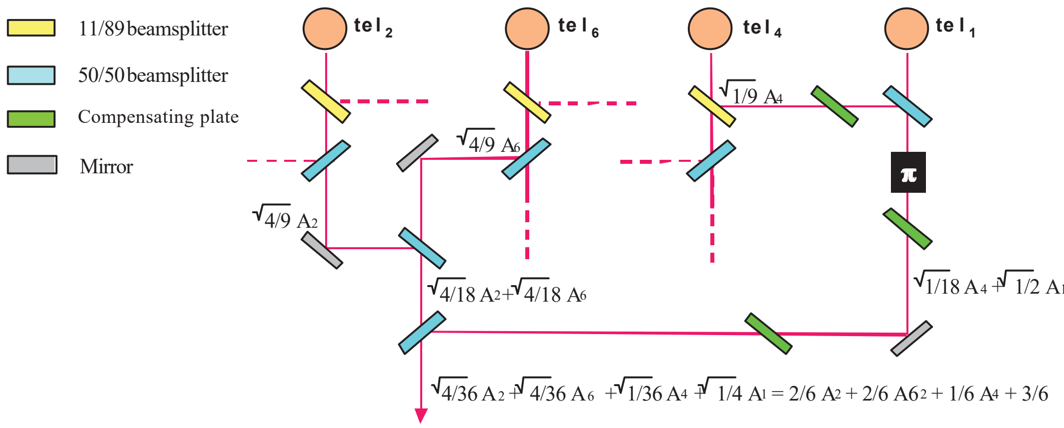

Figure 5 Beam-combining principle of the 3-GAC nulling interferometer

4.2 Beam-combiner design

The nulling beam combination function is performed in the central hub flyer, in 4 stages :

- First stage — even pupil beam combination (2, 4 & 6) with an amplitude ratio of 2.
- Second stage — odd pupil beam combination (1, 3 & 5), with the amplitude ratio 1 of even pupil. The GACs combinations are established by this stage.
- Third stage — final 3 GAC recombination, including an inter-GAC modulation function.
- Fourth stage — the spectrometers, detectors and fringe sensor beam combinations are implemented on this stage.

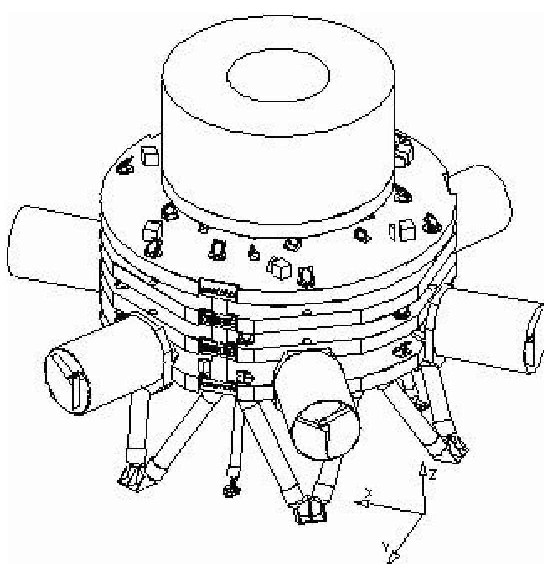

Figure 6 Hub mechanical architecture

On the First stage, adjustable delay lines are implemented at the entrance level of each beam, in order to balance the initial OPD biases detected by the fringe sensors. Flux matching devices are also needed, before beam combination, to ensure correctly balanced beam intensities.

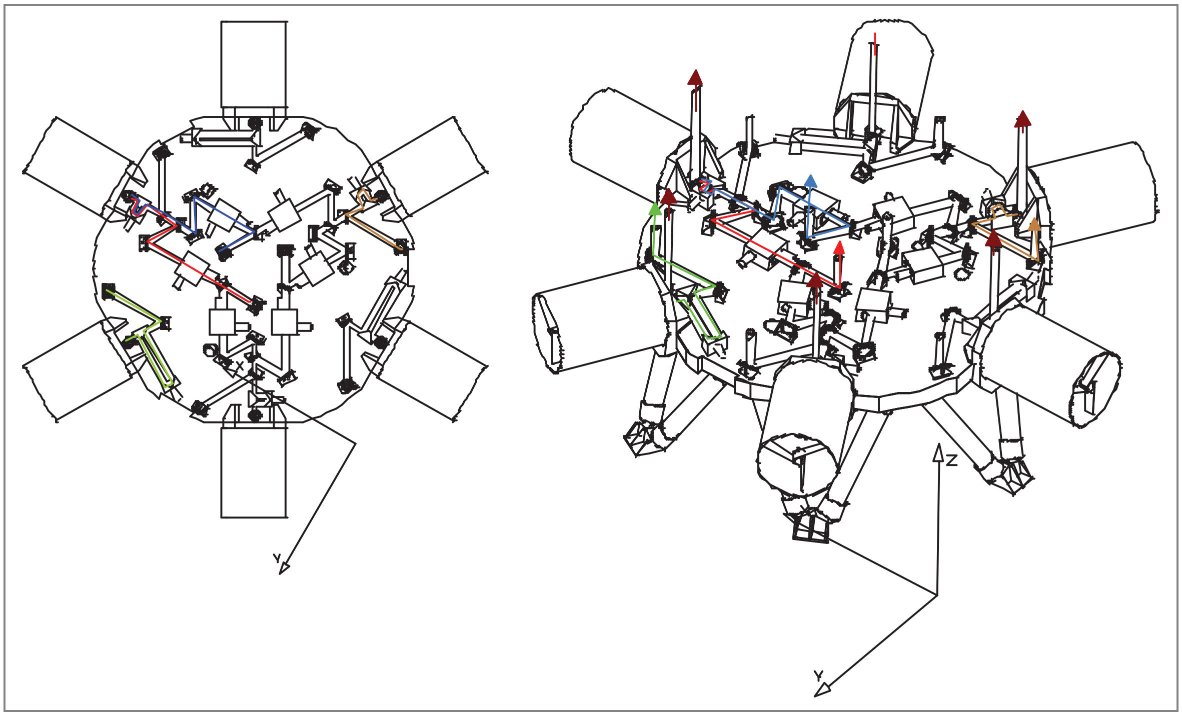

Figure 7 Beam-combiner 1st stage

On the second stage, the optical bench combines the beams received from pupils 1, 3 and 5 with part of the flux received respectively from pupils 4, 6, and 2, and introduces a π phase-shift into each of the resulting combined beams, which are then sent up to the third stage.

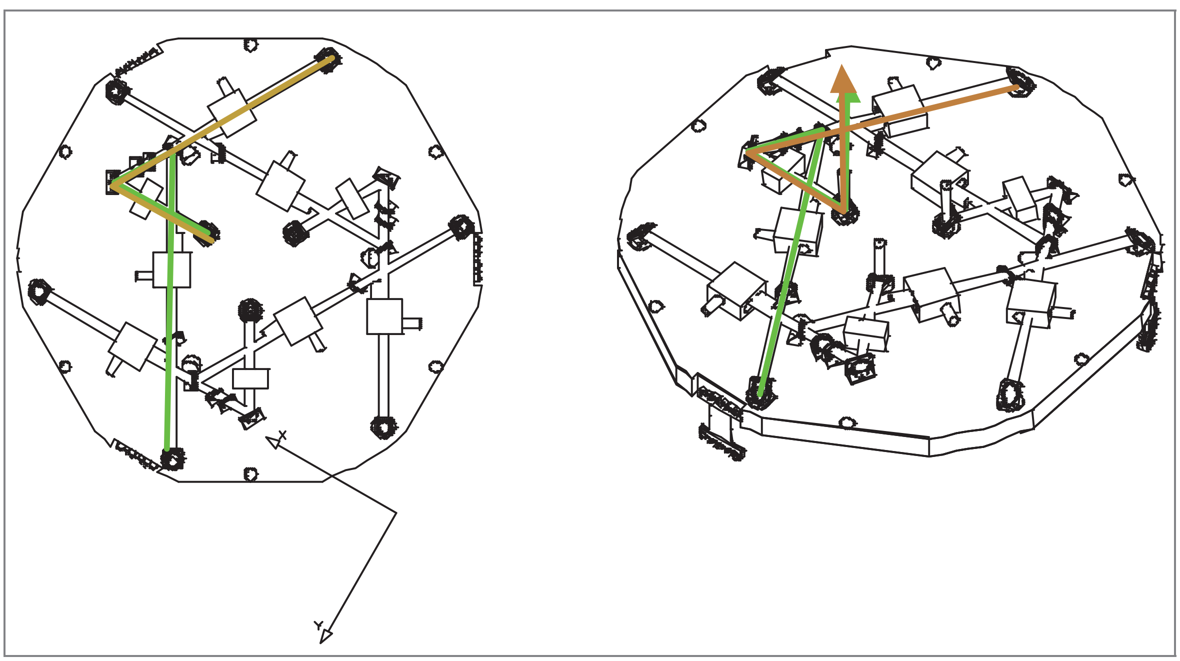

Figure 8 Beam-combiner 2nd stage

The following figure illustrates the accommodation of the optical elements which constitute the third beam-combining stage of the interferometer. At this level, the three outputs from the second stage are spatially filtered, and are then recombined via a modulating delay line, before being deflected vertically to the detector and fringe sensor stage.

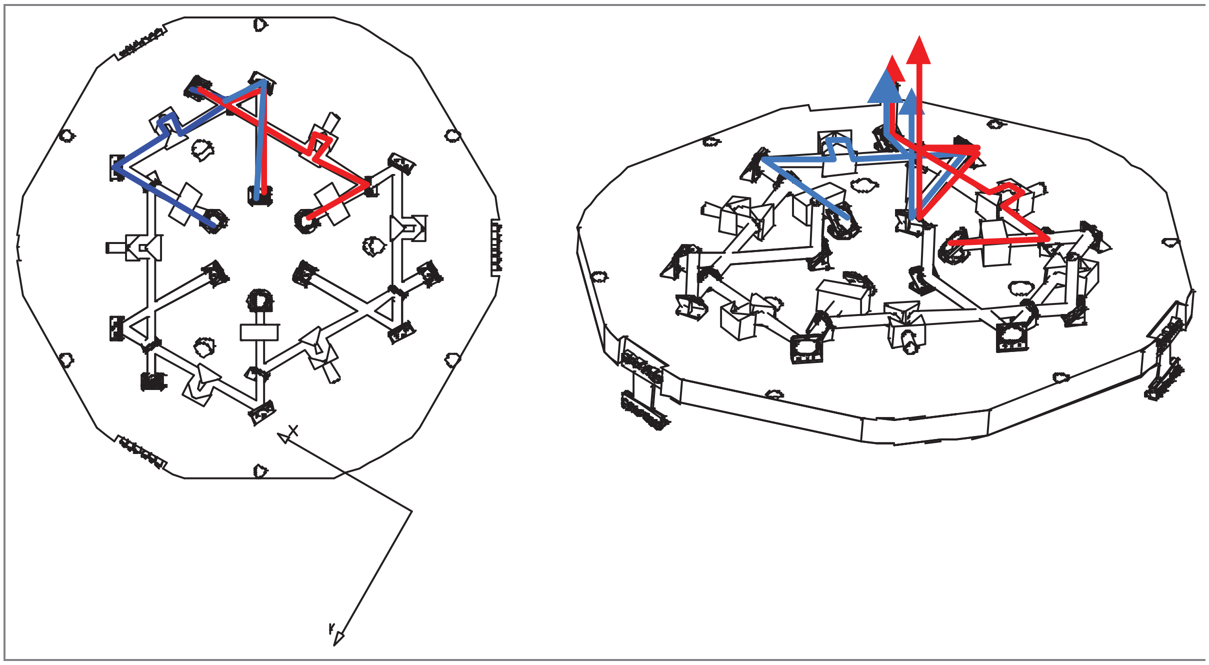

Figure 9 Beam-combiner 3rd stage

The final stage is used to accommodate all of the science detector focal planes, the spectrometers (represented by prisms in the following figure) and the fringe sensor combining components, prisms and detectors.

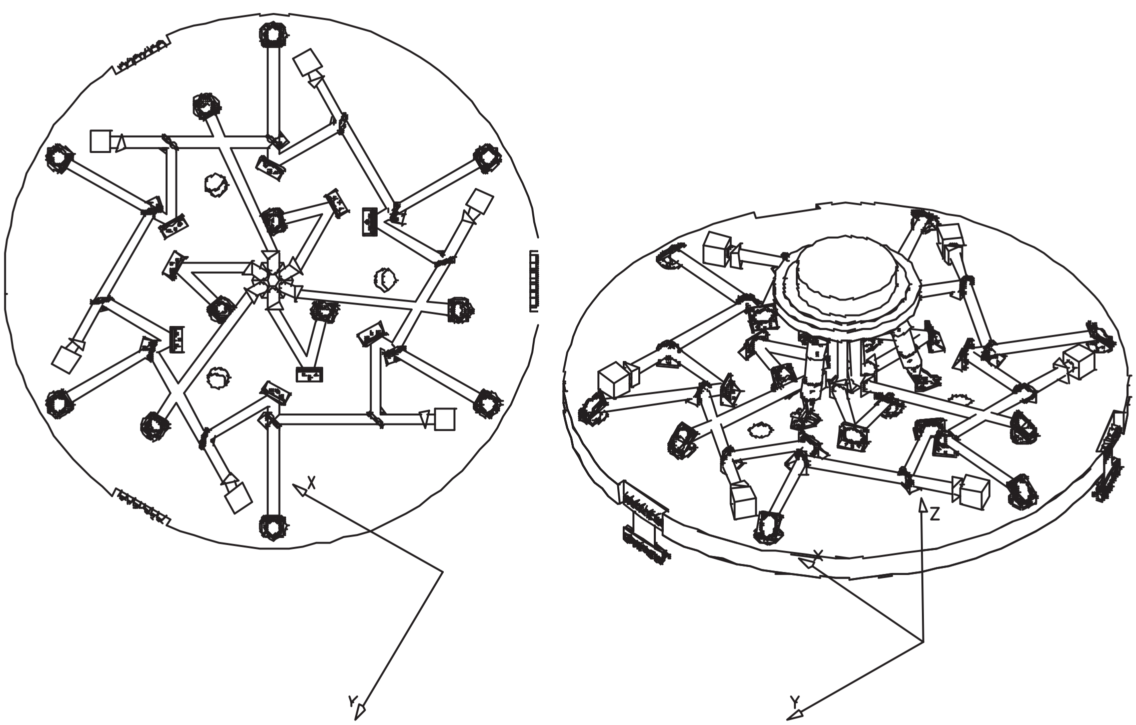

Figure 10 Beam-combiner 4th stage

From a mechanical point of view, each stage is supported by three flexible blades, ensuring a quasi-isostatic mount with adequate decoupling from thermo-elastic distortions induced by any of the other stages. The focal plane stage is located at the top of the hub (optimal shielding from solar flux) to facilitate its cooling to ~6 K.

The whole hub mechanical architecture has been selected in order to favour mechanical stability. The second strong objective was to choose a mechanical housing for the complex optical paths within the hub which could, by construction, respect the need for equal and symmetric optical paths. In addition, due to the high number of optical components with severe alignment requirements, accessibility to each of them is an important issue for the simplification of AIT procedures.

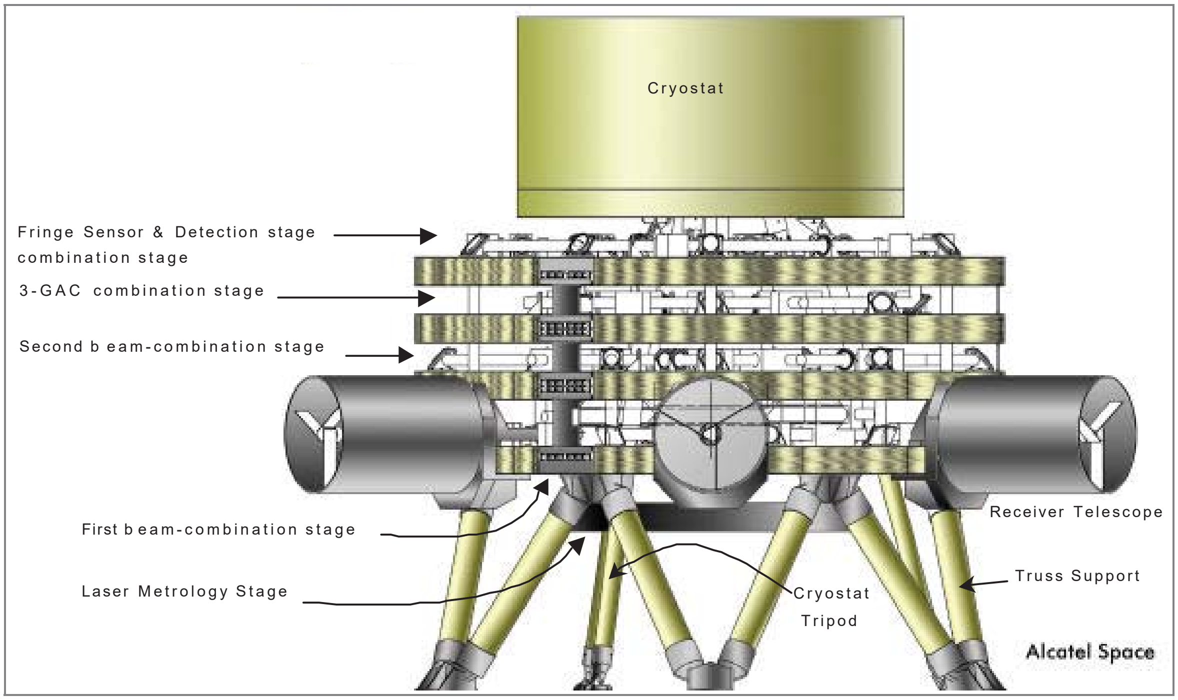

Figure 11 Beam-combiner mechanical architecture

5 CONCLUSIONS

For the first time in history, a major effort has been devoted to the system-level study of a space mission which will enable scientists to make direct detections of Earth-like planets in orbit around nearby stars, and furthermore which could enable us to detect the presence of organic or water-based life as we know it.

DARWIN will also be capable of operating as a “classical” imaging interferometer, by taking advantage of the potentially large baselines between the elementary collecting telescopes in order to obtain high angular resolution images, using the so-called “aperture synthesis” technique. This capability should open up completely unexplored realms of observational astrophysics, enabling scientists to explore in detail, for the first time, the interior of such objects as proto-planetary and proto-stellar disks, and active galactic nuclei.

The Darwin mission is likely to become the most ambitious science project ever undertaken by ESA and will, over the coming decade, call on the development of a large number of challenging technologies, relying on a high degree of collaboration within European space industry.

Among the notable achievements of the Alcatel Space study, it has been possible to determine that …

- ➯ a 6 x 1.5m telescope interferometer configuration is capable of achieving the scientific ambitions of the mission, using a single Ariane 5 launch and an orbit in the vicinity of L2,
- ➯ the steady state operating temperature of the optics can be kept below the required level of 40 K using passive cooling techniques,
- ➯ high accuracy sensors and µN FEEP thrusters should enable the free-flying spacecraft to be controlled to within nanometric optical path differences and milli-arcsecond pointing accuracies,
- ➯ nulling mode rejection ratios of between 10^5 and 10^6 should be achieved for on-axis stellar sources,
- ➯ within the 5 year mission lifetime, more than 100 Earth-like exoplanets could be detected, of which around 1/3 would be observed in spectroscopic mode,
- ➯ the nulling mode beam-combiner could also be used for imaging observations of extended sources down to the ~ 15^{th} magnitude.

The results of the ALCATEL SPACE study have thus shown that the initially chosen system requirements can be satisfied, and that the DARWIN mission could provide the expected scientific data return, in particular that corresponding to the highly challenging task of detecting and spectrally analysing "Earth-like" exo-planets orbiting nearby stars.