Darwin – The Infrared Space Interferometry Mission

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Darwin is a suggested ESA Cornerstone mission, with the express purpose of achieving unprecedented spatial resolution in the infrared wavelength region, leading to new astrophysics discoveries and the carrying out of the first direct search for terrestrial exoplanets. The detection and study of the latter promises to usher in a new era in science and will have an impact on a broad spectrum of science and technology.

Introduction

ESA already identified interferometry in space as an important topic in its original Horizon 2000 plan. Consequently, a number of conferences/workshops were held during the 1980s in order to define the scientific case, and even then the search for terrestrial exoplanets figured prominently. When an external survey committee made its recommendations for the extension of the Horizon 2000 Programme (Horizon 2000+), in response to technology developments worldwide, they identified interferometry from space as a potential Cornerstone candidate for the new programme.

Within the interferometric context, three topics were identified for further study:
– Astrometry.
– The search for terrestrial exoplanets, including characterisation of their properties and atmospheres and the possible detection of biospheres through remote sensing.
– Astrophysical imaging at a spatial resolution 2 – 3 orders of magnitude higher than that foreseen with the Next Generation Space Telescope (NGST).

Of these, the first was considered to be (relatively) 'simpler' to implement and subsequently resulted in the GAIA mission proposal and study. The Darwin study concerns itself with the two latter concepts, and during the mission definition phase the possibility of addressing both topics – exoplanets and imaging – with a single mission was given great weight.

To address fully the recommendations of the Horizon 2000+ Survey Committee for Darwin, it is necessary to:
– directly detect exoplanets
– define and observe the fundamental requirements for life as we know it
– define and observe signposts for the existence of life as we know it.

Below we describe the 'model mission', resulting from the system-level scientific and industrial study, that can fulfil these requirements. The version of Darwin that finally flies may depart significantly from this model mission, in the light of possible collaborations (see below). We also outline the intended technology-development schedule, the necessary pre-cursor programmes, and a possible framework for collaboration with other space agencies.

Ground-based observations of exoplanets

The last five years have seen the detection of many planets beyond our Solar System. Since the first detection of a planet around 51 Peg, reported by Queloz and Mayor in 1995, several groups have added about 30 planets to the map in our immediate neighbourhood in the Galaxy. The so-called 'indirect' technique used provides very little information about the planet itself (essentially its minimum mass, because the planetary orbit's inclination to our line of sight is unknown). The reflex motion in the parent star with respect to the common centre of mass of the star-planet system caused by the planet's gravity is observed as a periodic Doppler shift in the stellar spectrum over a relatively long period of time. The ground-based method's precision therefore depends on the accuracy with which we can measure the star's spectrum and is currently limited to a of a few ms^{-1}, allowing the detection of planets like Jupiter (12 ms^{-1}) or Saturn (3 ms^{-1}). It therefore appears unlikely that this method could be used to infer the presence of Earth-type planets. The lower limit eventually expected to be attainable is more plausibly a planet about the size of Uranus, but at significantly smaller distances.

Nevertheless, important results have been and are being achieved with this method, including the detection of the first planetary system upsilon Andromedae, which contains three planets with minimum masses of 0.77 $M_{Jupiter}$, 2.11 $M_{Jupiter}$ and 4.61 $M_{Jupiter}$. The planets so far discovered are also found mainly to have short orbital periods – something that has been clearly demonstrated to be a selection effect caused by the period of time during which observations have been carried out being relatively short. Consequently, as time passes, longer and longer periods are picked up, and there are now a number of confirmed planets in orbits with periods of a few years. Theorists, however, have problems explaining the formation of the 'hot Jupiters' – the massive planets orbiting very near their parent stars – as well as the high eccentricities possessed by the majority of the confirmed planets.

Another 'indirect' ground-based method is to obtain astrometric data and thus track a star's path across the sky, measuring the wobble introduced by the rotation around the common centre of mass of the star-planet system. Reports of the detection of planetary companions to some nearby stars have been legion during the last century. Both Barnards star and 61 Cyg have several times become the central objects of planetary systems, but none of these observations have ever been confirmed. In contrast, Hipparcos data have recently provided upper masses for a number of planets, including 51 Peg. ESA's GAIA mission promises statistical surveys of massive planets over large distances. The micro-arcsecond wobbles introduced in the solar proper motion across the sky, as viewed over distances of order 10 pc are, however, too small to be detected by this mission. Moreover, if a system involves more than one planet, there is a difficulty in characterising the planets (orbital period, mass) uniquely and unambiguously.

The scientific case for studying terrestrial exoplanets

The scientific case for Darwin is easy to state, but complex to describe. The phrase *to detect and study Earth-type planets and characterise them as possible abodes of life,* summarises the case nicely, but nevertheless does not project the complete picture. The simple fact is that Darwin is not only an astronomy mission, but also contains elements from geophysics (including atmospheric physics), biophysics, organic chemistry and philosophy and the humanities. Being so cross-disciplinary, therefore, the mission can also address the question:

"Are we alone in the Universe?"

which is one of mankind's longest standing quests. Although this question has been the topic of vigorous philosophical and religious debate for centuries, we have finally arrived at a point where technology has advanced sufficiently to allow it to be properly addressed.

In order to answer questions like:
– How unique is the Earth as a planet?
– How unique is life in the Universe?

we need to observe other stars and directly determine the existence and characteristics of any accompanying bodies. This has hitherto been impossible because of the influence of the star on the attempts to observe any planet circling it.

Definition of an unambiguous signpost for life is another matter completely. First we need to define what is life, and then to determine how that life affects its environment. Finally, we need to define observables that can be obtained with the level of technology foreseen for the mission. In the context of Darwin, we have so far avoided the first of these questions by instead specifying the mission requirements based on life as we have observed it on Earth. We thus disregard speculation about life forms based on a chemistry different from that found on our own planet. We then try to imagine the differences that would occur if life were nonexistant on Earth, and to use information on how life disturbs the equilibrium in the Earth's atmosphere as our criterion.

To fully answer the questions raised above, we need to:
– Detect planets within the 'life zone' (term coined by Frank Drake), i.e. the orbital radii where water is found in a liquid state surrounding other stars. In the Darwin study, the life zone is defined in terms of a black-body temperature and a range, and does not a priori take into account atmospheric pressure, etc. This assumes, of course, that life is based on the existence of liquid water.
– Determine the planets' orbital characteristics, which means that we need to repeat the observations several times.
– Observe the spectrum of the planet (Does it have an atmosphere?) and determine its effective temperature, total flux and diameter (emitting area x albedo).
– Determine the composition of the atmosphere viz. the presence of water and ozone/oxygen for an Earth-type planet, mainly inert gases

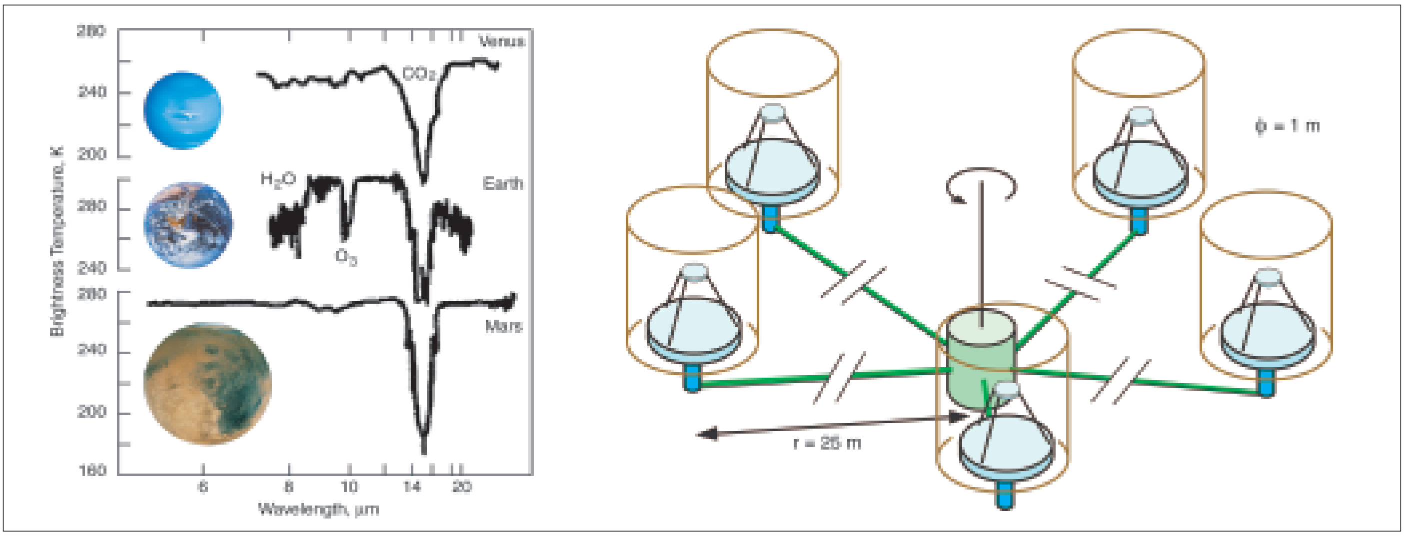


Figure 1. Left: Representative spectra (left) of the planets Venus, Earth and Mars at the relevant wavelengths. Right: schematic of the

for a Mars/Venus-type planet and hydrogen/methane atmospheres for Jupiter-type planets (Fig. 1a)

The Darwin Science Advisory Group and the industrial study

ESA received the Darwin proposal in response to a Call for Ideas in 1993, and it was among the mission concepts selected for a system-level industrial study. It can be briefly described as a nulling interferometer comprising five 1 m-class telescopes, flying at a distance of about 5 AU from the Sun (to reduce the background radiation from the zodiacal dust). It was specifically designed for the detection and study of terrestrial exoplanets (Fig. 1b). A subsequent reevaluation of the dust emission in the inner Solar System led to the currently favoured orbit at about 1 AU.

The Darwin community prepared for the coming study activity by holding its first (European) workshop in Toledo, Spain, in March 1996. To advise ESA on Darwin-related matters, a temporary external advisory body – the Darwin Science Advisory Group (SAG) – was formed in early 1997. This group was first tasked with aiding in the preparation of the scientific specification for an Invitation to Tender (ITT) for industry, and arrived at the end of 1997 at the following specification:

– Major Goal I: to detect Earth-like planets orbiting nearby stars and to set constraints on the possibility of the existence of ‘life as we know it’ on these planets.
– Major Goal II: to provide imaging in the 5 to 28 micron band, with spatial resolution an order of magnitude better than that expected of the Next Generation Space Telescope (NGST).

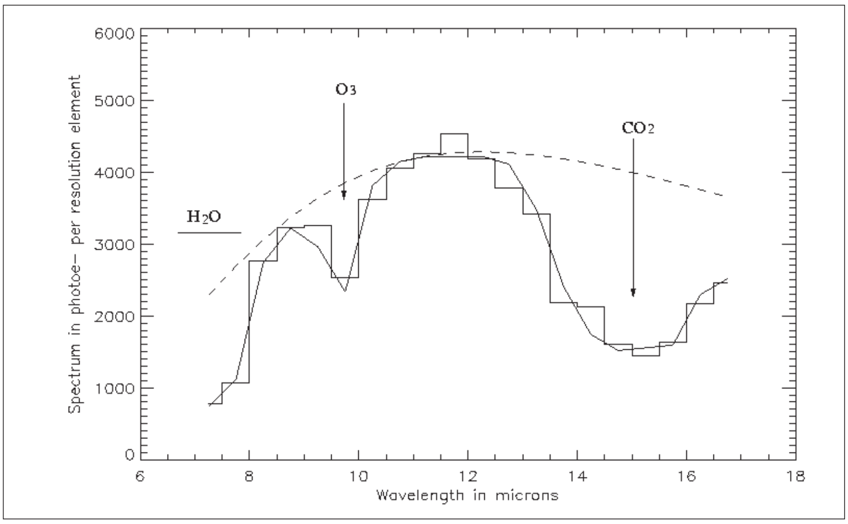
More specifically, these targets were quantified as:

– Directly detecting an Earth-like planet at a black-body temperature close to 300 K, circling a G0V star at a distance of at least 10 pc (preferably 20 pc) with a signal/noise ratio of 5-10 in a reasonable integration time (less than 30 h)
– Characterising the detected planet physically through determination of its orbital elements, requiring observations at several epochs.
– Obtaining the planet’s thermal spectrum with a spectral resolution large enough (more than 20) to determine its atmospheric composition (Fig. 2).

One item here requires further comment, namely the selection of the thermal spectrum. In principle, one could also use the reflected spectrum of the planet and detect signatures of life within the visual or ultraviolet spectral bands. As explained below, however, observations in these wavelength bands would severely constrain the mission in a number of ways.

This specification was provided in the ITT offered to European industry in September 1997. After a tender evaluation of industrial proposals to ESA, Alcatel Space Division (at the time Aerospatiale Space Division) was selected, thus concluding the evaluation phase. Their study ended in mid-April 2000.

Figure 2. The Earth’s spectrum as it would appear observed with Darwin from a distance of 10 pc. The spectral range has been specified here as 7 to 17 microns. Ideally, one would like to observe a larger part of the spectrum in order to detect the thermal continuum on both sides of the H^2O and CO^2 lines.



The specific goals of the feasibility study were to:
- define a model mission that would be able to achieve the scientific goals
- identify a technology development programme
- identify the necessary pre-cursor missions (ground- and space-based).

The current mission-model baseline consists of six free-flying 1.5 m telescopes, arranged in a hexagonal configuration, with in the centre of the array a beam-combining satellite equipped with optical benches for both the 'nulling' and the 'imaging' parts of the mission axis – the so-called 'Robin Laurance configuration', in honour of the first Darwin Study Manager who tragically passed away in 1999, developed by A. Karlsson at ESTEC (Figs. 3 a,b). All components in the optical path, from the main mirrors to the output of the beam-combination unit, need to be passively cooled to less than 40 K, something that Alcatel's thermal modelling indicates is possible if the mission is flown in an orbit far from heat sources such as the Earth (Fig. 2). To minimise the influence of the zodiacal dust emission at 10 micron, the observing zone is a 40 deg cone around the anti-Sun axis. This planar configuration (good thermal environment) combines transfer optics of manageable size with a good rejection ratio of the central null, and can use both internal modulation and simple translational movement for discriminating, for example, exo-zodiacal light from the signature of an Earth-type planet. It also allows, in principle, for both an imaging and a nulling mission to be flown on the same spacecraft.

The six telescopes, the hub beam-combiner satellite and a separate power and communications spacecraft are all foreseen to be launched by a single Ariane-5 vehicle into a direct transfer orbit to the L2 Lagrangian point in the Sun-Earth system.

The nulling-interferometry technique

As mentioned above, directly detecting exoplanets is essentially a matter of contrast and dynamic range. The star around which the planet revolves is going to be more than 10^9 times brighter than the planet, if we chose to observe in visual light. The planet is also going to be very close – an Earth-type planet in an orbit in the 'life-zone', i.e. 1 AU from its sun, is going to be 1 arcsec away at a distance of 1 parsec. Unfortunately, the closest potential target we have is α Centauri at 1.1 parsec. To get a suitable number of targets, we have to reach out to at least 10 parsec, and preferably 25 parsec, thus making the life zone viewable at 0.1 and 0.04 arcsec, respectively. This is for solar-type targets; for K- and M-type stars, which will dominate our sample, the separation will be much smaller, because of observing planets within the zone where we expect water to be liquid. It is clear that, using conventional telescopes, our detectors would have to handle an impossible dynamic range in order to separate out the planetary light.

The problem is alleviated by going to the infrared, where the relative contrast between primary and planet drops several orders of magnitude (Fig. 4). This was first pointed out by Bracewell (in 1978) and Angel et al. (in 1986), who also pointed out the advantage of using lines of the H_2O,O_3 and CO_2 molecules as tracers of life as we know it. Kasting et al. (in 1985) and Legér et al. (in 1993) have demonstrated that O_3 is a very nice tracer for O_2, since the former has a logarithmic dependence on the concentration of the latter.

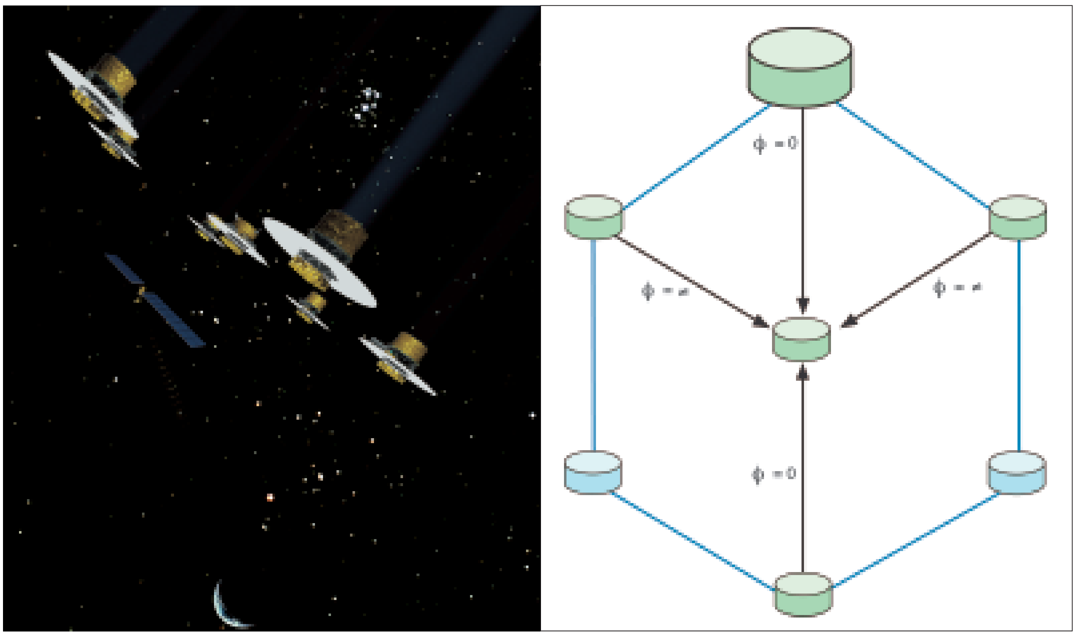


Figure 3. Left: Artist's impression of the current Darwin configuration, seen orbiting at the Sun-Earth L2 point (courtesy of Alcatel). Right: the planar Robin Laurance configuration, which is the current Darwin baseline

We then have suitable tracers for Earth-type atmospheres in a wavelength band between about 6 and 20 microns. We can still only allow 10^{-6} of the stellar light to remain in the input feed to our spectrograph if we are to have any hope of detecting the planetary light and registering its spectrum in a reasonable time.

It can be shown that coronographic methods on monolithic telescopes do not suffice to accomplish such an extinguishing of light at the relevant spatial scales. To overcome this hurdle, the 'nulling interferometry' technique is baselined for Darwin. A nulling interferometer (also known as a Bracewell interferometer) can best be described by considering two telescopes. By restricting the beams coming from each of the telescopes to the diameter of the point spread function, and after making the light beams parallel, we can introduce a phase shift of $\phi = \pi$ into one of the ray paths, which will achieve destructive interference on the optical axis of the system (in the combined beam). At the same time, we will have constructive interference a small angle θ away. This angle θ depends on the distance between the two input telescopes (Fig. 3b). The output of this system is a set of interference fringes or 'map', with a sharp 'null' in its centre. By placing the central star under this null, and the zone where for example H_2O will be liquid under a bright fringe, one can in principle search for planets in the 'life zone'. Now, by using more telescopes, we can achieve a symmetric pattern around the star, with a deep central null on top of the star. The actual shape and transmission properties of the pattern around the central 'null' depends on the configuration of, and the distance between the telescopes.

Essentially, if we had an ideal case with a star and a single planet and no disturbing sources, such as exosolar zodiacal dust, i.e. dust left over from collisions between asteroids, comets and suchlike in the target system, the detection of a positive flux would imply that a planet is present, if the star is well and truly 'nulled out'. This means that the detector could consist of a single element. We wish, however, to also carry out spectroscopy with as high a resolution as possible, and a linear array is thus indicated. In the real world, there is of course a significant amount of background radiation coming from dust. The zodiacal dust in our own Solar System is strong enough to be seen as a bright band (in visible light) from dark locations on the ground. At a wavelength of 10 microns, this radiation is dominant (the zodiacal dust temperature within the 'life zone' will also be close to 300 K, and thus the peak of the emission is radiated around 10 microns) and thus a significant background signal is present in the inner Solar System.

When observing the Solar System at interstellar distances, the zodiacal dust is actually about 400 times brighter than the Earth at these wavelengths. To separate out the planet's signal from this background, one needs to modulate the signal from the planet and from the zodiacal dust at different frequencies. This is done either by switching between different combination schemes (certain geometrical arrangements of the telescope array), or by moving the individual telescopes around, or both.

Technology development and precursor missions

One prominent goal in the Alcatel study was to identify a technology-development programme leading to a Darwin mission as soon as possible. Consequently, an ambitious technology-development plan has been initiated, including space qualification and verification, in the context of ESA's SMART programme. Activities planned for the next three years include development and construction of:
– high-stability optical benches
– active optics control

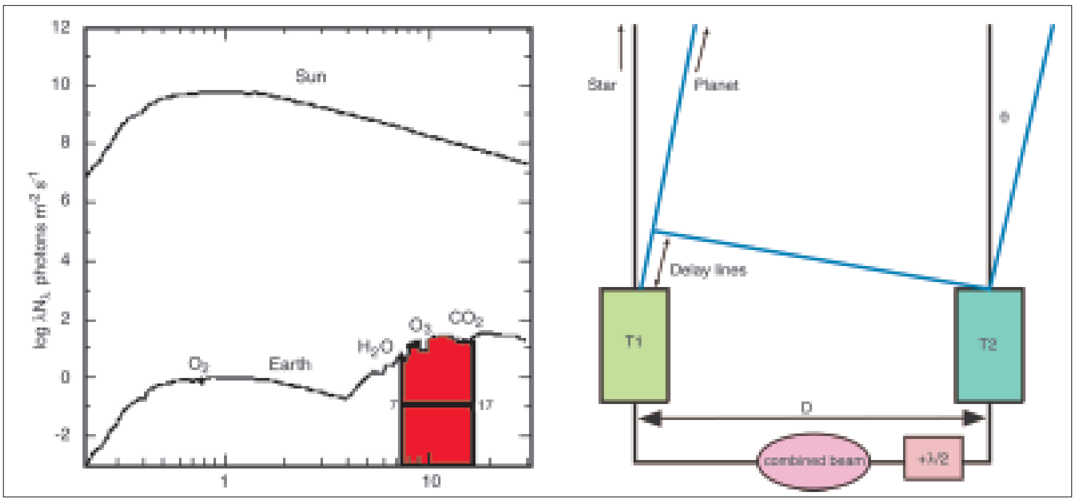


Figure 3. Left: contrast between the solar flux and the Earth as a function of wavelength in microns, with the Darwin spectral band indicated (adapted from Angel, Cheng & Woolf, 1986). Right: a two-telescope nulling interferometer, where the angle theta depends on the distance D (drawing courtesy of IAS, Orsay, France)

- fibre-optic wavefront filtering, with single-mode fibres operating in the 10 micron region, and an investigation into the phasing capabilities of fibres
- integrated optics, optical components for nulling and imaging interferometry
- achromatic phase shifters for nulling interferometry
- detectors and cooling systems
- satellite formation flying, deployment and control, with a local GPS system for 1 cm positional accuracy
- ultra-high-precision (laser) metrology
- Field Electric Emission Propulsion (FEEP) technology.

One of the key issues is to develop and verify 'nulling' interferometry. It is currently not deemed necessary to demonstrate this in space, but a representative breadboard with an associated simulator providing the necessary input signals has to be designed and built within the next few years. An associated pre-cursor activity is observation of the exo-zodiacal light from target systems. This can be carried out from the ground, using the breadboard in conjunction with a large enough interferometer, e.g. using the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory (ESO). By using the breadboard together with the VLTI, its qualification would also provide much-needed scientific information. Plans for such a collaboration between ESA and ESO are well advanced and a joint ESA/ESO science group has been formed.

One of the most challenging technological aspects of the Darwin mission is that it requires several spacecraft to be flown in close proximity with centimetre precision. This control is foreseen to be provided – during an observation – with micro-Newton FEEP thrusters (the greatest disturbing force in an L2 orbit is the differential solar photon pressure on the individual spacecraft). Spacecraft deployment and source acquisition will be effected using milli-Newton FEEP thrusters. A local GPS system keeps the spacecraft within one centimetre of their intended positions, while a laser metrology system measures their actual positions to within 5 nm. A separate channel in the interferometric system will observe the fringes from the central star in the target system – which is nulled out in the 'science channel' – and since the observed systems are all relatively nearby, there is no lack of photons for tracking the fringes. This information is fed into the control loop of the interferometer's two 'nulling' and imaging circuits, as well as into the attitude and control systems of the individual spacecraft. This technology requires a precursor mission to actually test:

- the deployment, acquisition of observing positions, and control of a spacecraft flotilla
- the metrology components – fringe tracker, laser system
- the software/hardware of the control system
- milli- and micro-Newton thrusters.

Consequently, this technology is also being introduced into the SMART precursor mission programme. It should be noted in this context, that most of the new technologies required for Darwin will also have other valuable applications, the flotilla flying (for communication satellite purposes), interferometry (Earth observation of many kinds) and the ultra-high-precision laser metrology being good examples. This provides an additional source of support for Darwin, since many of the technology-development items can be partially or totally funded from outside the Science Programme. This is also an added factor in ensuring that such developments can be carried out relatively quickly.

International collaboration

Space interferometry is also being pursued elsewhere outside Europe, the two most obvious examples with the capability to search for exoplanets being SIM (Space Interferometry Mission) and TPF (NASA's Terrestrial Planet Finder). SIM is an optical interferometer which will use relative astrometry to attempt to detect 'super-Earths', i.e. planets of 5 to 10 Earth masses, through an indirect method. Another of its goals is to carry out 'nulling interferometry' to one part in ten thousand at visual wavelengths. Because of these targets, SIM can be considered a pre-cursor mission to Darwin and TPF.

TPF has the same objectives and uses the same technology as foreseen for Darwin. Given that both projects are extremely complex, require very ambitious technology-development programmes, and are likely to be very expensive, it would make sense for NASA and ESA to cooperate. Discussions have in fact begun regarding a possible joint mission, to be launched sometime around 2012.

Acknowledgments

This article reflects several years of work by the Darwin Science Advisory Group (SAG), including that of a number of experts who participated in the concept's development. We all pay tribute to our colleagues Jean Marie Mariotti and Robin Laurance, who passed away during the study but who will be with us in spirit to the completion of the task before us.