OVERVIEW OF THE DARWIN MISSION

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1. MISSION OVERVIEW

The search for terrestrial extrasolar planets is a topic within the cosmic vision program of ESA [1]. It involves a scope of different missions leading to DARWIN, an optical space nulling interferometer [2], with a foreseen launch in 2015. The ambitious mission objectives are: a) detection and analysis of planets orbiting nearby stars, searching for earth-like conditions and life and b) high resolution imaging by aperture synthesis.

The detection problem is essentially a matter of contrast and dynamical range. Considering planets in the habitable zone (HZ), the star and planet will be very near each other on the sky while the star outshines the planet with up to 9 to 10 magnitudes in the visible and 6 to 7 magnitudes in the IR. The problem of how to find the dim planet next to a bright star will be solved by reducing the level of contrast by observing in the infrared and by using a technique known as Nulling Interferometry. Essentially the signals from the separate telescopes are combined such as to blank out the strong signal from the star and to show only the light coming from the regions around the star.

The required rejection ratio to achieve the mission objectives is 10^5 over a band from 6µm to 18µm. The configurations of five and six telescopes were optimized on the basis of highest achievable modulation efficiency [3][4].

2. HABITABLE ZONE

The Habitable Zone (HZ) around a star is defined as the zone around a star within which starlight is sufficiently intense to maintain liquid water at the surface of the planet, without initiating runaway greenhouse conditions that dissociate water and sustain the loss of hydrogen to space, see J. Kasting et al. [5]. The planet's effective temperature T_p depends on the temperature T_* and thus brightness of the star, the planet's albedo A and its distance to the star a_p.

$$T_p = \frac{(1-A)^{1/4} T_*}{\sqrt{2}} \left(\frac{R_*}{a_p} \right)^{1/2} \tag{1}$$

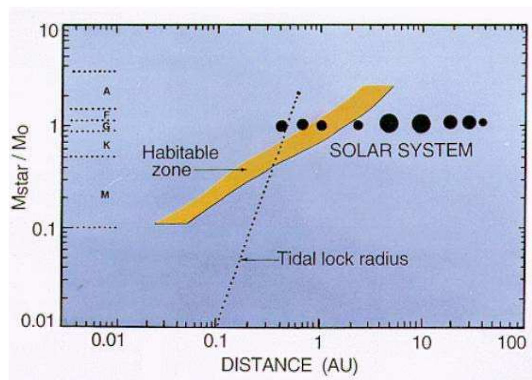

Fig. 1: Habitable zone for different star types [5].

Using this equation we determine the Habitable Distance (HD), as the distance where a planet like earth-would encounter the same effective temperature, equivalent to a distance of 1AU around the sun. The HZ extends further outwards as well as inwards from that distance. The calculation of the HD is based on the luminosity of the star. The model is based on work by Kasting et al [5].

$$a_{HD} = \left(\frac{T_*}{T_\Theta} \right)^2 \frac{R_*}{R_\Theta} = \left(\frac{L_*}{L_\Theta} \right)^{1/2} \tag{2}$$

While a debate about the extent of the HZ around different stars is going on, in our work and this paper Kasting's work is used to determine the HZ. Other models are being established. Once they become consolidated the calculations will be updated.

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3. TARGET STAR CATALOGUE

A list of stars, mainly from the Gliese and Jahreiss catalogue of nearby stars (1991), was compiled by A. Leger and M. Ollivier for the Darwin feasibility study. Two selection criteria were adopted: i) spectral type GKM within a distance of 25 pc, ii) stars within a cone of aperture ± 45° of the ecliptic plane and the anti-solar direction. An updated version carried out [6] grouped the stars by spectral types and now contains a sample of about 800 stars. For the G Type stars the properties of the stellar targets was revised [7] through consultation of existing data archives.

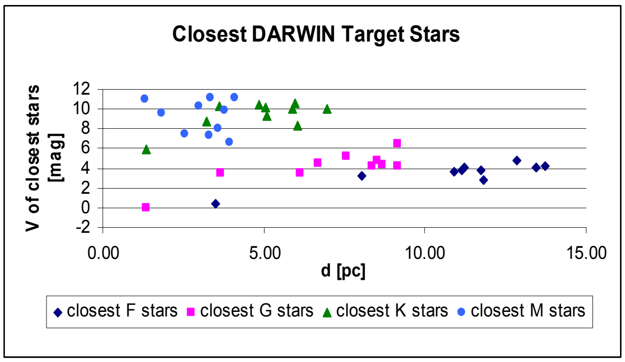

Fig. 2: V magnitude of the closest DARWIN target stars by stellar class.

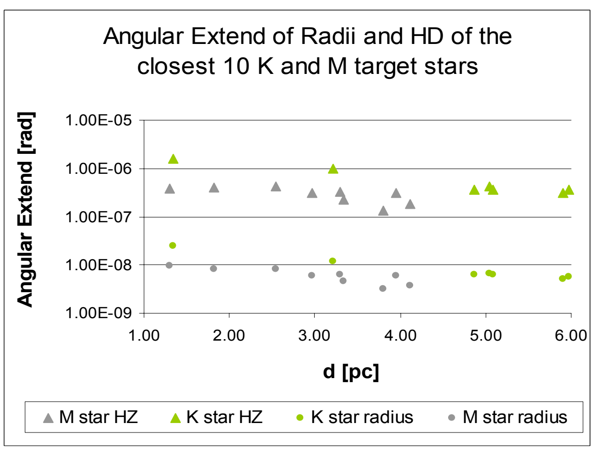

Fig. 3: Angular extent of the radius of the star and their corresponding HD for the closest 10 target stars for each stellar type.

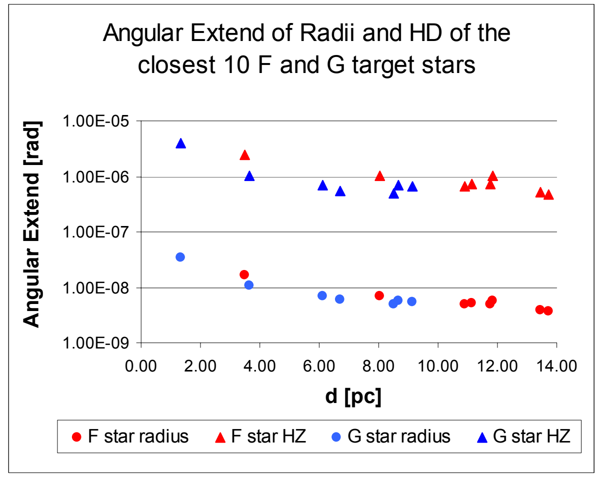

Fig. 4: Angular extent of the radius of the star and their corresponding HD for the closest 10 target stars for each stellar type.

4. SELECTION CRITERIA

The selection criteria for the updated DARWIN stars from the HIPPARCOS catalogue lead to a total of 807 stars. The criteria are listed below:

- distance smaller than 25 pc for F,G,K, M stars
- coordinates between –45 and +45 ecliptic declination (refers to the 45 degree cone in anti sun direction)
- Stellar luminosity class (main sequence: incl also sample with undetermined luminosity class, thus especially the sample of K and M stars will be smaller once the luminosity class is determined)
- B-V index for main sequence stars
- Stars with magnitudes smaller than 12 in V detected by HIPPARCOS. As DARWIN concentrates on brighter/closer star the completeness of the HIPPARCOS sample is an issue for densely populated area but the catalogue will be updated once the new Gliese catalogue is available. Darwin focuses on close-by and bright stars, thus dim stars are ranked to lower priority in the star sample.

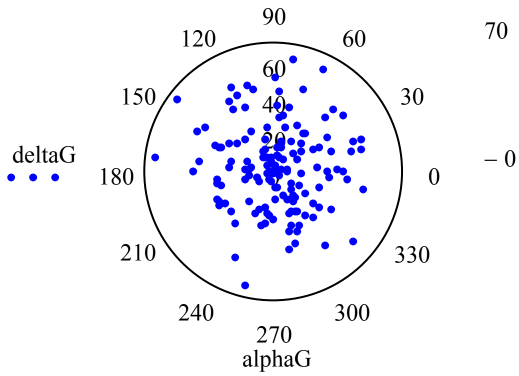

Fig. 5 Spatial distribution of DARWIN G target stars

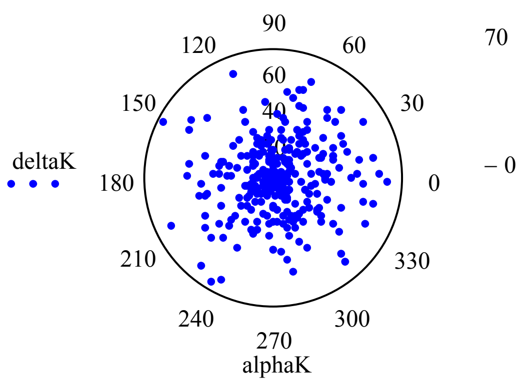

Fig. 6. Spatial distribution of DARWIN K target stars

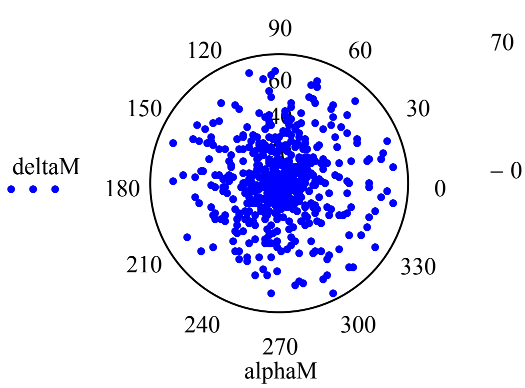

Fig. 7 Spatial distribution of DARWIN M target stars

The influence of exo-zodiacal clouds is an important constraint for planet detection with DARWIN. This issue will be addressed by GENIE (Ground-based European Nulling Interferometry Experiment)[8][9]. The prime objective of GENIE is to gain experience with the design, construction and operation of a nulling interferometer, as preparation for the DARWIN mission. GENIE will be particularly sensitive to warm circumstellar dust as it operates at mid-infrared wavelengths and thus provides the opportunity to investigate the properties of the DARWIN target stars [9] [10][11].

5. FREE FLYER CONFIGURATION

Nulling Interferometry was originally proposed by Bracewell and McPhie in 1979 [12]. The basic concept is to sample the incoming wavefront from the star and its planet with several telescopes that individually do not resolve the system. One interferes the beams while adding an achromatic phase shift of 180 degrees in one arm or several arms of the interferometer array, to achieve destructive interference for an on-axis source. Instead of the usual bright fringe, this places a dark fringe on the detector at the place where the bright star would be.

The output of this system is an intensity level, modulated by the transmission map, which has a sharp 'null' in the centre. By placing-the central star under this null, and the HZ under a bright fringe, one can search for planets in the HZ. The use of more than two telescopes allows generating symmetric pattern around the star, with a deep central null for the star. The actual shape and transmission properties of the pattern around the central null depends on the configuration, 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 exo-solar zodiacal dust, i.e. dust left over from collisions between asteroids, comets and such, in the target system, the detection of a positive flux would imply that a planet is present. That means that the detector could consist of a single element. However to carry out spectroscopy and a linear array is used. In the real scenario there is a significant amount of background radiation coming from dust. The zodiacal dust in our own solar system is strong enough to be seen from the ground in dark locations in the visible light as a bright band. At a wavelength of 10μm, this radiation is dominating. The zodiacal dust temperature within the Habitable Zone will be close to 300 K and thus the peak of the emission is radiated around 10μm and a significant background signal is thus present in the inner Solar system.

If we were observing the Solar system at interstellar distances, the zodiacal dust would actually be about 400 times brighter than the Earth at these wavelengths [13]. In order to separate out the signal of the planet from this background one need 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 a combination of both methods [14].

DARWIN could be implemented in a wide variety of configurations, constrained by the number of telescopes and the necessary background and starlight suppression. Mariotti and Mennesson [15] proposed a method called “chopping” that suppresses large-scale diffuse emissions form a zodiacal cloud by observing alternately the signals of different sub-array interferometers with narrower nulls. The configuration for five and six telescopes was optimized on base of the highest achievable modulation efficiency [13][4]. Two sub-interferometers use telescopes of equal size that are positioned regularly spaced on a circle. The optimum telescope positions on the circle are derived through mathmatical programming. Absil [4] and Menesson [15] have identified various optimum configurations for a space based Interferometer configuration. Once the planetary location is known, the baseline and orientation of the array can be chosen to yield the maximum modulation efficiency at a selected wavelength. The results were confirmed by our study. Fig. 8 to 13 illustrate the behaviour of the different configurations.

5.1 5 telescopes spaced on a circle to provide highest modulation efficiency

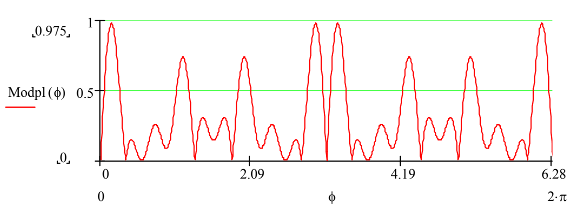

Fig. 8. Modulation function of a point source signal at the HD from its parent star due to a full rotation of the telescope array.

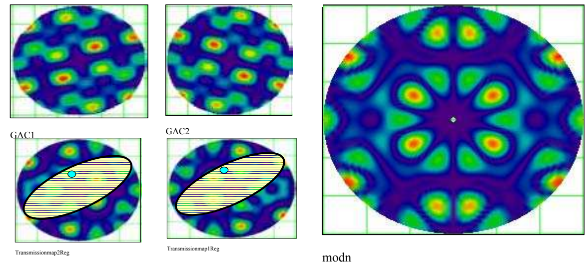

Fig. 9: (left) transmission map of the 5 telescope configuration with the highest modulation efficiency [4], output of the sub-nulling interferometer (upper panel), the two asymmetric maps conjugated by central symmetry after beam combination with +/- Pi/2 phaseshift (lower panel). (right) generated modulation map shows a bright spot of the Sun’s diameter in its center: Sun at 10pc, Maps: diameter 500mas, Rejection value: 10^5

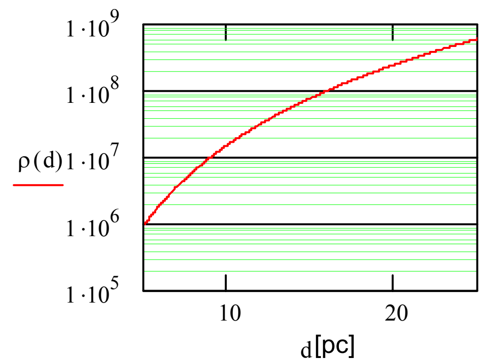

Fig. 10. Rejection of the starlight ρ(d) over distance from the observed system d.

5.1 5 telescopes regularly spaced on a circle

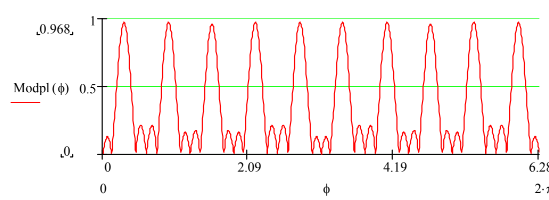

Fig. 11. Modulation function of a point source signal at the HD from its parent star due to a full rotation of the telescope array.

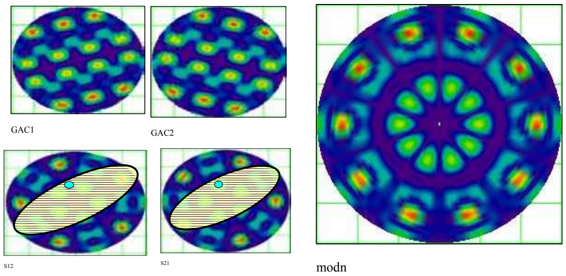

Fig. 12: (left) transmission map generated by 5 telescopes equally spaced on a circle [4], output of the sub-nulling interferometer (upper panel), the two asymmetric maps conjugated by central symmetry after beam combination with +/- Pi/2 phaseshift (lower panel). (right) generated modulation map shows a bright spot of the Sun's diameter in its center: Sun at 10pc, Maps: diameter 500mas, Rejection value: 10^5

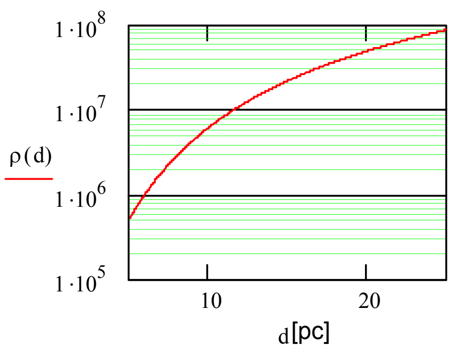

Fig. 13. Rejection of the starlight ρ(d) over distance from the observed system d.

5.1 6 telescopes with optimized modulation efficiency distributed on a circle

The step from 5 to 6 telescope provides a substantial gain in stellar rejection. Fig.3 shows an example of the modulation of a planetary signal of a configuration called Liégeoise [4]. The rejection is 10^8 for a sun at 10pc.

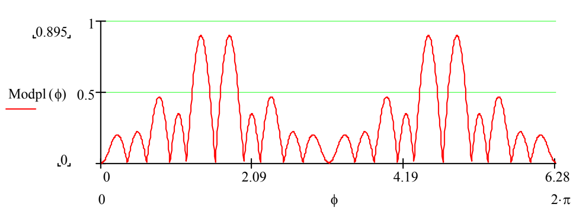

Fig. 14. Modulation function of a point source signal at the HD from its parent star due to a full rotation of the telescope array.

Information on the spatial distribution of the source can be found by temporal encoding, e.g. by characteristic modulation of the signal emitted by an off-axis source through rotation of the array. A planet can then be detected trough the intensity, the characteristic shape and wavelength dependence of its modulated signal. A transmission map, of e.g. an interferometer array, is a transmission efficiency as a function of the coordinates of the source in the sky in reference to the telescope plane. The properties of transmission maps are used in the trade-off between different array configurations.

6. IR OBSERVATIONS

Future space based missions like DARWIN and a version of TPF concentrate on the region between 6µm to 18µm, a region that contain the CO_2, H_2O, O_3 spectral features of the atmosphere. The presence or absence of these spectral features would indicate similarities or differences with the atmosphere of telluric planets.

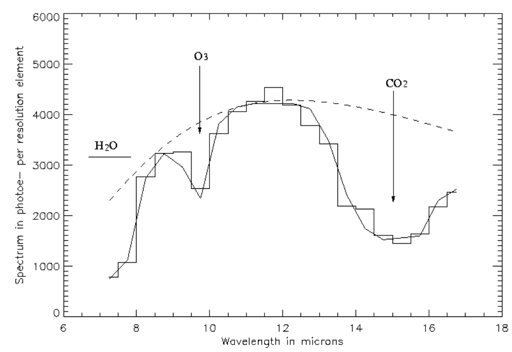

Fig. 15: Calculated IR spectrum detectable by the DARWIN mission [16]

- 9.6µm O_3 band highly saturated, poor quantitative indicator, excellent qualitative indicator for traces of O_2
- 15µm CO_2 band
- 6.3µm H_2O band or its rotational band from 12µm out into the microwave region, Observations (8µm to 12µm H_2O continuum) allow estimations of surface temperature of Earth-like planets. Atmosphere of planets warmer than 310K opaque in this region (continuum absorption by water vapour)

- 7.7µm band of CH_4 (potential biomarker for early-Earth type planets)

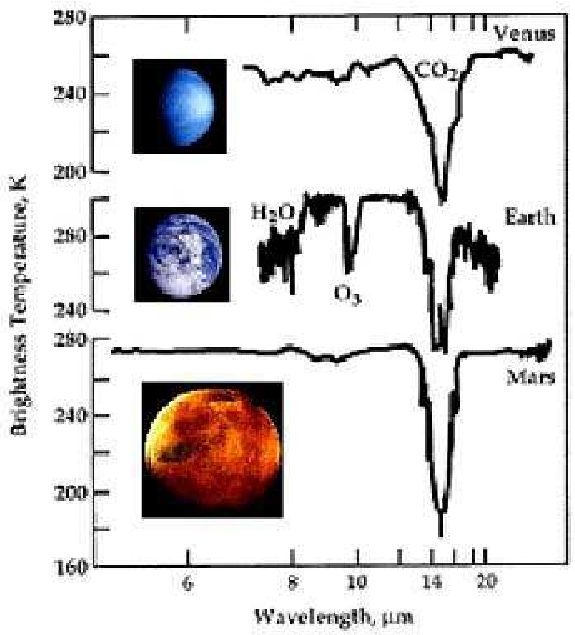

Fig. 16. Thermal infrared spectra of Venus, Earth and Mars. The 15µm CO_2 band is seen for all three planets. Earth also shows evidence of O_3 and H_2O [16].

The mid-IR spectra can give the planet's albedo, the temperature of the observable emitting regions and thus the planet's size [17] [18]. In the thermal part of the spectrum, the shape gives a measure of the temperature of the object examined. Visible to near-IR spectra offer higher spatial resolution, are minimally affected by temperature and therefore able to determine the abundance of atmospheric species. However the visible/near-IR continuum does not give direct indication of the planet size because of the possible albedo range. Through the IR spectrum one can detect carbon dioxide at low spectral resolution.

The planets need to be characterized in terms of mass, orbital parameters, atmospheric composition and temperature. All this requires the repeated detection of a planet with a good signal to noise ratio. Having found distant planets, another key reason for observing in the infrared is the search for life. Life on Earth leaves its mark at these wavelengths.

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