Nulling Interferometry with IRSI-Darwin: Further Study of the Aperture Configurations

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Abstract: After a brief introduction to nulling interferometry, we emphasize the limitations of this technique for the detection of exoplanets, and the need for *internal modulation*, a recent technique for fast signal chopping. The principles of internal modulation are then discussed and illustrated with an example. Our contribution to the Darwin mission deals with the study of new aperture configurations using internal modulation. The best two configurations identified among an infinity of new possibilities are presented. As compared to the current Darwin configuration, the sensitivity to the planetary signal is improved by a factor of two, resulting in a fourfold speedup in the detection and characterization of exoplanets.

1 Introduction

Detecting an Earth-like exoplanet orbiting a Sun-like star at a few parsecs from us is a very demanding task because of the huge contrast and the very small angular separation between the two bodies. Furthermore, if we want to characterize an exoplanet by means of spectroscopy, the only way to do so is to observe the planet directly. Such observations are better carried out from space, in the mid-infrared, since the thermal emission of the planet peaks around 10 μm, providing a much lower contrast between the planet and the star in that waveband than in the visible range. Moreover, infrared spectroscopy is well suited to detect potential biological activity (Léger et al. 1996). Unfortunately, the ultimate angular resolution of infrared telescopes is badly limited by their aperture size: even with a 10 m-class telescope, an Earth-like exoplanet will be hidden in the diffraction pattern associated with its bright host star. This limitation can be overcome by means of nulling interferometry.

2 Principles of Nulling Interferometry

2.1 The Bracewell Interferometer

The first nulling interferometer was proposed by R. Bracewell in 1978. In this pupil-plane interferometer (Fig. 1), the delay lines are set so that at recombination the paths followed by the two beams are exactly the same for a target on the axis of the interferometer. A special device, called an achromatic phase shifter, is then used to get a destructive interference for the on-axis star.

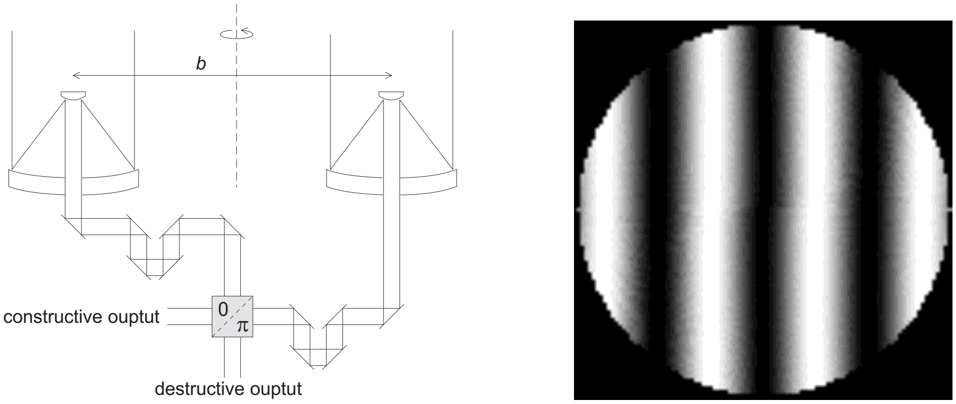

Figure 1: Left: Sketch of Bracewell's nulling interferometer. Right: Transmission map for the destructive output, with a dark fringe at the center of the 300×300 mas field of view ($b = 25$ m, $\lambda = 10\ \mu$m).

Since the only thing we measure is an integrated flux on a single pixel detector, we cannot distinguish between a bright planet on a gray fringe and a faint planet on a bright fringe. This is the reason why Bracewell proposed to rotate the interferometer around its line-of-sight, with a period of about one hour. The planetary flux is then modulated as the planet crosses bright and dark fringes in the transmission map, leading to a non-ambiguous measurement of its flux.

2.2 Limitations to the Bracewell Configuration

There are three main limitations to the detection of an exoplanet with a Bracewell interferometer. The first is related to the finite size of the stellar disk, and the two others to the thermal emission from the dust clouds surrounding the Sun and the target star.

- *Stellar Leaks.* Even with an ideal Bracewell interferometer, the light coming from the edges of the stellar disk is not perfectly cancelled because the central transmission of the interferometer varies as θ^2, where θ represents the angle to the optical axis. Considering the typical case of a Sun-Earth system seen from 10 pc at $\lambda = 10\ \mu$m, and setting the distance between the two telescopes to about 25 m so that the Earth-like planet stands on the first bright fringe, the overall rejection rate of the interferometer is only 10^3, while the contrast between the two bodies is about 5×10^6. This problem can be overcome by using more than two telescopes: with three in-line telescopes (Degenerated Angel Cross), or with four telescopes standing on a circle (Generalized Angel Cross), the transmission rate can vary as θ^4, which is enough to cancel the central star by a factor of 10^7.

- *Local Zodiacal Cloud.* The second limitation is due to the thermal emission of the zodiacal cloud, which is heated to about 300 K at 1 AU from the Sun. The total zodiacal flux collected by 1 m-class telescopes is about 1000 times larger than the flux from the exoplanet, but since it is not modulated by a rotation of the array, it can be canceled by signal processing. However, the real problem comes from its high photon noise, and above all from the long-term fluctuations of its brightness. These fluctuations can be confused with the slowly modulated flux of the planet unless fast signal chopping is used.

- *Exo-Zodiacal Emission.* The last major problem comes from the exo-zodiacal cloud surrounding the target star. Considering a dust cloud similar to ours, its integrated flux is about 300 times larger than the planetary signal, but this time it is also modulated by rotation of the array (unless it is seen pole-on), so that it can be confused with the exoplanet.

2.3 Internal Modulation

The principle of internal modulation is to divide a telescope array into two (or more) nulling interferometers in order to perform fast modulation between their outputs (Mennesson and Léger 2000). The sub-interferometers are formed by dividing the light beams collected by each telescope (Fig. 2a-b). Both have a real entrance pupil, which means that the phase shifts applied to their light beams are restricted to 0 or π, and both achieve a θ^4 transmission rate.

By recombining the two outputs (Fig. 2c) on a lossless beam-combiner, we get two new transmission maps which are both asymmetric, although symmetric to each other with respect to their center (Fig. 2d). Therefore, an extended source with central symmetry such as the exo-zodiacal cloud has the same contribution in both outputs. On the other hand, the planet has two different contributions because when the planet lies on a bright zone in the first map, it is located on a dark zone in the second map. Thus if we alternately detect these two outputs on a common detector, we get a final signal where only the planetary part is modulated. The modulation map (Fig. 2e) shows which places on the sky are strongly modulated (bright zones), and where there is no modulation at all (dark zones).

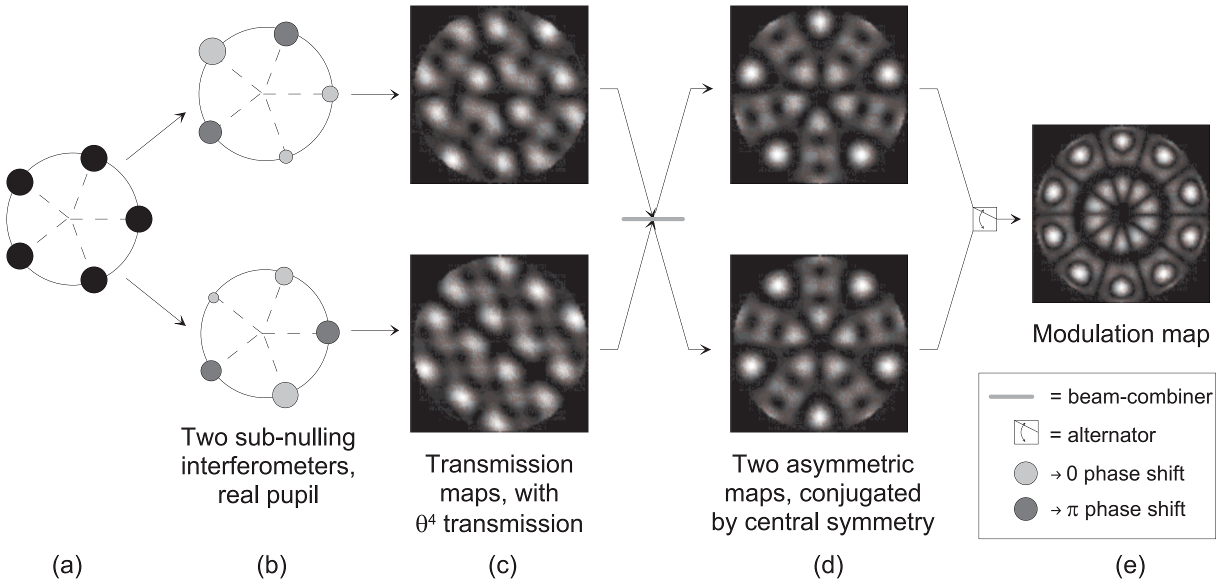

Figure 2: Principle of internal modulation.

A key advantage of internal modulation is that the switching between the two outputs can be done at a high frequency, so that there is now a clear distinction between the rapid modulation of the planetary signal and the slow fluctuations of the background. Another advantage of internal modulation is that in principle, the array need not be rotated any more. In practice, some small rotations should still be applied to ensure a good sky coverage. Note that two modulated signals can be formed with the two outputs, depending on the order of switching between them. Therefore, two detectors are needed to collect all the information, in order to get an optimal signal-to-noise ratio. The planetary part of the signal is then isolated by means of synchronous demodulation.

3 Aperture Configurations for the Darwin Mission

The aperture configurations for the Darwin mission are mainly based on the so-called Robin Laurance (RL) configurations, defined by Karlsson and Mennesson (2000). In these configurations, the telescopes must stand on a circle, in a common plane, in order to reduce thermal coupling between the telescopes and to avoid long delay lines. Another constraint is to have equal size telescopes in order to reduce manufacturing costs.

3.1 Current Baseline

The current baseline for the Darwin mission is a hexagonal configuration performing internal modulation between three sub-interferometers (Karlsson and Mennesson 2000). The main limitation to this configuration is its weak modulation efficiency: the maximum modulation efficiency is indeed only 30%. This means that when the position of the planet is known, and the array tuned to place the planet on a bright zone with a high modulation efficiency, only 30% of the planetary signal is actually modulated. The other 70% are lost. Even worse, when the location of the planet is not known, the mean modulation efficiency is as low as 12%.

In order to improve this low efficiency, a systematic search for new aperture configurations has been undertaken and has led to a large number of new possibilities (Absil 2001): the two best ones are presented hereafter.

3.2 Further Study of RL Configurations

Circular configurations with five and six telescopes have been comprehensively studied. The best of them seems to be the so-called "bow-tie", with six telescopes in an irregular hexagonal shape. It performs internal modulation between two identical sub-interferometers (GACs). Its maximum modulation efficiency reaches 65%, that is, more than twice that of the original hexagon. Its mean modulation efficiency is still rather low (13%). With this new configuration, the time required for characterization of exoplanets by spectroscopy is reduced by a factor of four. The only drawback of this new configuration is that the modulation map is not at all uniform (Fig. 3), so that an exoplanet could be missed unless up to six small rotations are applied to the interferometer in order to cover the whole habitable zone surrounding the star.

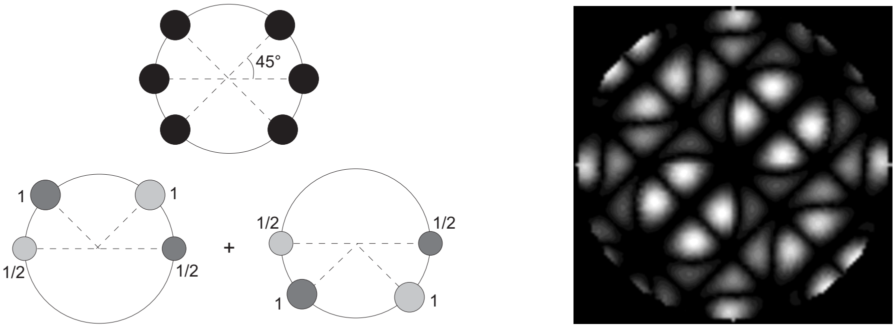

Figure 3: Left: the bow-tie configuration with its two sub-interferometers (Generalized Angel Crosses). Right: modulation efficiency of the bow-tie configuration over a 300×300 mas field of view for an array radius of 25 m and observation wavelength of 10 μm.

This configuration has also the big advantage to significantly reduce the complexity of the beam-combination optics, because only two sub-interferometers are used instead of three. This reduces the number of detectors from six to two. Moreover, only two 50:50 beam-splitters are needed to form the sub-interferometers.

3.3 Further Study of Linear Configurations

Linear configurations with four or five telescopes have also been studied. The best of them seems to be a new version of the OASES configuration, with internal modulation between two interlaced Degenerated Angel Crosses. This configuration needs only four telescopes, but of different sizes. Its maximum modulation efficiency is 51% while the mean efficiency reaches 20%, with a good sky coverage (when three maps shifted by 60 degrees are superposed).

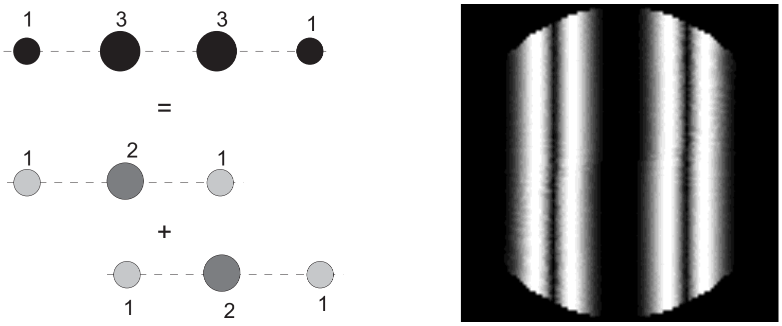

Figure 4: Left: the new OASES configuration with its two sub-interferometers (Degenerated Angel Crosses). Right: modulation efficiency of OASES over a 300×300 mas field of view for a total length of 50 m and observation wavelength of 10 μm.

However, a major difficulty associated with linear configurations is that the light beams have to be reflected on neighboring telescopes in order to equalize the external optical path delays. This could exaggeratedly constrain the control laws on their position. In fact, it is not clear yet whether circular or linear configurations are preferable, because both have advantages and drawbacks whose technical consequences still need to be evaluated. An important criterion for the final configuration choice will probably be the capability of each configuration to reconstruct an image of the planetary system from the nulled output.

3.4 Inherent internal modulation

A new kind of internal modulation, called *inherent* internal modulation, has recently been proposed by Karlsson (personal communication). Its goal is to perform internal modulation in a more simple way, without an extra beam-combiner (Fig. 2c-d). This can be done if the transmission maps of the two sub-interferometers are already asymmetric, and conjugated to each other by central symmetry. In order to achieve non-symmetrical transmission maps, the two sub-interferometers must have a complex entrance pupil (proof in Absil 2001, p.125-128), and the central symmetry relation between the two transmission maps can easily be obtained by taking opposite signs for the applied phase shifts (see Fig. 5). Fast modulation can then be carried out as before by alternately detecting the two asymmetric outputs.

The main advantage of inherent modulation is that the two outputs can be formed separately, while they were formed simultaneously on a beam-combiner in the case of classical internal modulation. Consequently, one can decide to alternately send *all* the collected light to each sub-interferometer, and to alternately detect their outputs on a single detector, so that two detectors are not needed any more to collect all the light.

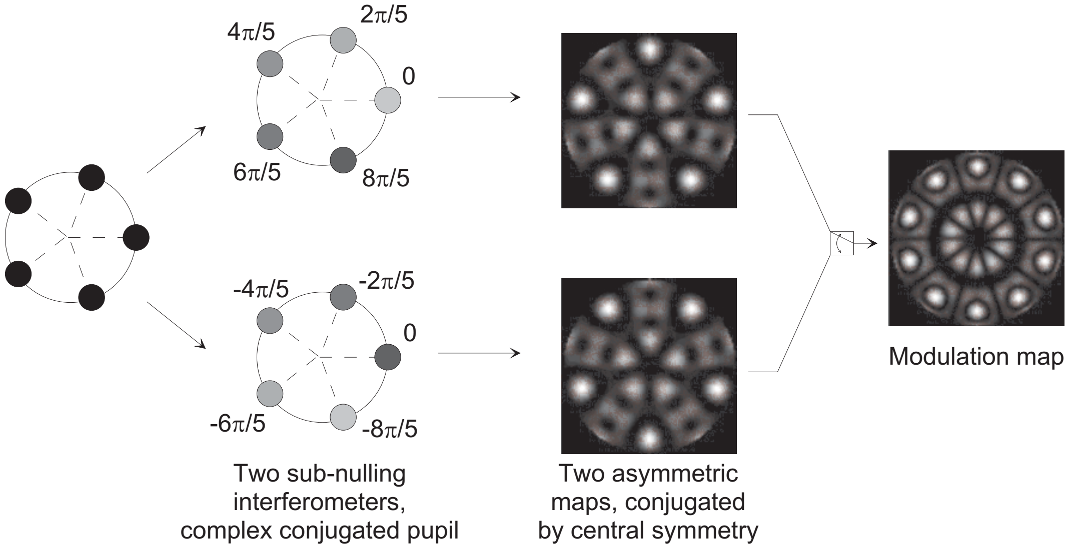

Figure 5: Principle of inherent internal modulation.

Unfortunately, the maximum modulation efficiency of circular configurations with inherent modulation does not exceed 40%, because the sub-interferometers are formed of at least 5 telescopes, so that a third order recombination scheme is necessary. On the other hand, inherent modulation is well suited to linear configurations since only four telescopes are needed. The maximum modulation efficiency can almost reach 50% (see Absil 2001, p.102-107).

4 Conclusions

In this paper, we have shown that new aperture configurations can significantly increase the efficiency of the Darwin interferometer, and thus allow the study of many more planetary systems than initially anticipated. However, the road-map of theoretical and technological developments leading to the final Darwin design is still very long. A crucial parameter to the feasibility of the mission is the level of exo-zodiacal light. The design of a ground-based nulling interferometer on the VLTI could not only validate the technique of nulling interferometry but also provide the very much-needed scientific information about the prevalence of dust clouds around nearby stars.

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