Performance analysis of a space-based multiple-telescope nulling interferometer for DARWIN

The European Space Agency’s infrared space interferometry mission called DARWIN is dedicated to the investigation of Earth-like extrasolar planets orbiting bright stars. A multi-aperture interferometer fed by free-flying telescopes allows spectroscopic analysis of the weak planet signal which could give hints on the possibility of the existence of Earth-like life. However, for a Sun/Earth-like constellation at an interstellar distance of some 50 light years, a star light suppression of about 60 dB is required to make the weak planet signal visible.

In this paper we investigate the nulling capability of a space-based Robin Laurance interferometer in the case of stochastic disturbances of the array geometry and of stochastic alignment errors of the optical components, which both will be actively controlled. Mismatch of amplitude transmission, optical path length, and polarization transmission among the interferometer arms is taken into account.

We numerically analyze Sun/Earth-like constellations in the wavelength range of 6 to 18 microns and calculate the expected value of the star light rejection ratio for the Robin Laurance geometry. It is shown that maximum standard deviations of only $\sigma_p = 2 \text{ nm}$ and $\sigma_A = 5 \times 10^{-4}$ for the differences in optical path length and amplitude transmission can be allowed to obtain a rejection ratio of $R = 60 \text{ dB}$. These and other exemplary numerical results confirm the extreme requirements for interferometer uniformity and give a quantitative insight into the dependence of the attainable rejection ratio on individual and/or combined interferometer imperfections.

Keywords: DARWIN; interferometry; nulling; telescope arrays; Robin Laurance configuration

1. Introduction

The objective of the European Space Agency’s infrared space interferometry mission called DARWIN is to detect and analyze Earth-like extrasolar planets (Leger et al., 1996). The prospect is to detect absorption lines of potential life indicators, like H$_2$O, O$_3$, or CO$_2$, by spectroscopic analysis of the radiation received from the planet in the infrared wavelength regime of 6 to 18 microns. The investigations, to be performed by an instrument positioned in an orbit at the second Lagrangian point, are focused on Sun/Earth-like constellations at interstellar distances of some 50 light years.
The instrumental problems to be solved stem from the close neighborhood of the star and the planet and from the high contrast between the two radiation sources. A nulling interferometer as suggested for DARWIN, in principle, provides both a high angular resolution to separate the planet from the star and a strong rejection of the star light. However, the large wavelength range of operation and the extreme requirements on interferometer uniformity are highly challenging demands on the interferometric instrument.

In this paper we investigate the nulling capability of a space-based Robin Laurance interferometer in the case of stochastic disturbances of the array geometry and of stochastic alignment errors of the optical components. We establish a system model describing the parameters influencing the rejection performance and analyze the suppression of the star light in the case of individual and/or combined stochastic interferometer imperfections.

2. The Robin Laurance nulling interferometer

In a nulling interferometer the light arriving from slightly different directions experiences significantly different transmissions when propagating through an interferometer as shown in Fig. 1 (Bracewell, McPhie, 1979). In the simplest arrangement, the sum of star and planet waves incident in the observation plane is received by two identical telescopes. One of the resulting signals is then changed in phase, and finally both signals are superimposed to obtain interference. Destructive interference for the star signal is obtained for a relative phase shift of half a wavelength between the two interferometer arms. In case of adjustment of the telescope positions, i.e. for a spacing of $L/(2 \Theta)$, the planet signal experiences constructive interference. As the input signals are not monochromatic, the required phase relation to null the on-axis star has to be realized by an achromatic phase shifter, i.e. independent of the input signal wavelength $\lambda$.

The optimum condition for the telescope spacing obviously can be only fulfilled for a single wavelength, the design wavelength $\lambda_0$, which should be chosen as the smallest wavelength of the interval considered.

In practice, the interferometer will consist of an array of more than two telescopes, where the number and the geometry depend on the required rejection ratio and on the star/planet constellation. Several geometries have been analyzed in the past (Mennesson, Mariotti, 1997; Wallner et al., 2001). Presently, the hexagonal Robin Laurance configuration seems to be the most suitable one (Karlsen, Mennesson, 2000). An artist's conception is shown in Fig. 2 (European Space Agency, 2001). The Robin Laurance configuration consists of six equal, free flying telescopes arranged in a hexagonal geometry, one in-plane hub satellite comprising the beam combiner, and possibly one out-of-plane master satellite. The advantage of this concept compared to the previous ones is that it allows internal switching of the interferometer's spatial transmission maps, which is required for distinguishing between exozodiacal dust clouds and planetary signals. Only four telescopes are operated at a time to form a nulling interferometer. Figure 3 shows the geometries and the source plane transmission maps of the three resulting arrangements.

In our investigations we arbitrarily define the planet's Cartesian coordinates as $(x_p, y_p) = (1 \text{ AU}, 0)$, where AU denotes an astronomical unit (the mean distance between Sun and Earth), and exemplarily analyze the interferometer as shown in the center column of Fig. 3. In order not to attenuate the already weak planet signal, the planet position should coincide with an interference maximum of the transmission map. This is attained if the diameter $d$ of the hexagon fulfills the condition $d = 2 \lambda_0/L = 40 \text{ m}$, where $\lambda_0 = 6 \mu\text{m}$ is the smallest wavelength of interest and $L = 50 \text{ LY}$ is the distance between the telescope array and the star (LY denotes light-year).

3. Performance analysis model

In the following we investigate the impact of imperfections on the rejection performance of a single-mode, multi-telescope nulling interferometer with a co-axial beam combining scheme. The general structure of such an instrument is shown in Fig. 4. The incident radiation is coupled to the propagation medium (fiber or free-space optics) by means of the receiving unit, i.e. by a telescope. The sub-beams then are affected in phase by achromatic phase shifters, which establish the phase relation required for star light rejection, nominally independent of the wavelength. For deep nulling, uniformity in amplitude, optical path length, and state of polarization of the signals to be combined is absolutely necessary. To this end these properties of the sub-beams are adapted by control units, the control signals of which are derived from various sensor systems not shown here and from the overall output signal. In the combining optics the individual sub-beams interfere, i.e. the output of the combining optics nominally carries only the planet signal. In the processing unit the actual science measurement is performed.

If all the system components work perfectly, nulling of the star light to the theoretical limit determined by the array geometry is possible. In a practical system, imperfections of the geometry and of optical components occur, leading to a reduced

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**Fig. 1.** Principle of a nulling interferometer ($e_1$ and $e_2$ denote the optical field strengths in the interferometer arms)

**Fig. 2.** An artist's conception of the Robin Laurance nulling interferometer for DARWIN