Exoplanet detection using a nulling interferometer

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Abstract: The detection of extra solar planets is a topic of growing interest, which stretches current technology and knowledge to their limits. Indirect measurement confirms the existence of a considerable number. However, direct imaging is the only way to obtain information about the nature of these planets and to detect Earth-like planets, which could support life. The main problem for direct imaging is that planets are associated with a much brighter source of light. Here, we propose the use of the nulling interferometer along with a photon counting technique called Dark Speckle. Using a simple model the behavior of the technique is predicted. The signal-to-noise ratio estimated confirms that it is a promising way to detect faint objects.

References and links

1. Introduction
In the last six years, more than fifty Jupiter-like planets have been reported. In every case their presence has been inferred from indirect measurements. Most of them have been found using
the Doppler technique, which measures changes in the star’s velocity due to the planet’s gravitational force. However, direct imaging will offer information hidden to other detection techniques and will allow us to observe Earth-like planets, which cannot be detected using other techniques [1]. The main problem for direct imaging is that planets are associated with a much brighter source of light. In the visible, where planets shine by reflection of starlight, the contrast ratio between a Jupiter-like planet and its parent star is about $10^9$.

To reduce this ratio, Hinz et al. [2] suggested using infrared (IR) wavelengths between 5 and 10 $\mu$m. In this range of wavelengths many young giant planets are self luminous and the star/planet intensity ratio, $R$, is about $10^6$. The advantages and drawbacks of the use of visible or IR light will be analyzed later on. In both cases, the star diffraction pattern at the planet location is still several orders of magnitude brighter than the planet peak [3]. Consequently, the star diffraction rings must be suppressed in order to detect a planet. As an example, for a wavelength of 600 nm and a 8 m telescope, a planet 1 AU from a star at 10 pc is located at the position of the fifth Airy ring of the star (0.1 arcsec). In the IR case, the resolution is lower and, thus, the planet is even closer to the star’s Airy core.

Several solutions have been proposed for the suppression of the star diffraction pattern, e.g. the nulling interferometer [4,5], a coronagraph with phase mask [3] or the use of a square transmission-weighted apodizing aperture in the telescope pupil [6]. Each technique offers some advantages and, of course, some drawbacks. The main disadvantage of the phase mask is its bandwidth limitation, while the square aperture technique does not make use of all the energy arriving from the planet. The nulling interferometer requires extremely precise control although interferometric techniques offer high spatial resolution with small apertures. Hence, such an instrument could detect Earth-like planets and perform spectroscopic analysis to look for features of water or ozone, which would indicate that the planet supported life. Consequently, here we choose the nulling interferometer, although this does not mean that the other techniques should be discarded. It is worthwhile to perform an analysis of the other techniques similar to that developed here for the nulling interferometer. Thus, the most suitable conditions for each technique could be found. Even, the combination of different techniques should be considered [6].

The main advantage of the nulling interferometer is that it allows the detection of light coming from the planet in a pixel where the light from the star is interfering in a destructive way. This is because the nulling interference condition is fulfilled for a particular scientific object, but for a different object this condition does not work. Most of the physical principles upon which a final nuller for exoplanet detection must be based, have already been experimentally validated. Hinz et al. have shown the feasibility of the nulling interferometer to suppress the star diffraction pattern: using images of Betelgeuse, light from an unresolved star almost disappears, while a source 0.2 arcsec apart remains [2]. Wallace et al. have achieved a deep and stable nulling of broadband thermal light [7].

We choose a scheme with two telescopes co-mounted on a rigid frame pointed at a star, with no need for path equalization. Although there are more complex configurations, such as that proposed by Angel to achieve good star suppression even when a long baseline is required (because the planet is close to the star or due to the use of IR wavelengths) [1], our analysis of the dark speckle technique can be easily generalized for any configuration.

The planet could be detected in a few hours integration if the atmosphere does not distort the incoming wavefronts [1,2]. The nulling interferometer could be put in space to avoid the atmospheric effects. Unfortunately this is a very expensive solution. A space-based nulling interferometer useful for searching for Earth-like planets will probably not be operational for at least two decades. However, the effect of atmospheric distortions can be compensated in ground-based instruments using Adaptive Optics systems. These systems are composed of a wavefront sensor, that measures the wavefront distortions, and by a deformable mirror, which dynamically compensates for them in real time. Unfortunately, it is impossible for an adaptive optics system to fully restore the imaging performance of a ground-based telescope due to the
finite signal and measurement noise in the wavefront sensor, the finite number of degrees of freedom in the deformable mirror, time delays between sensing and correcting, anisoplanatism, etc. Hence, a technique providing the best signal to noise ratio, SNR, should be used. This fact encouraged us to combine the detection of visible or IR light in a compensated nulling interferometer with the use of the Dark Speckle technique proposed by Labeyrie [8,9]. In the next section this technique will be briefly described and the system gain will be obtained using a simple model. In section 3, the feasibility of detecting exoplanetes by the dark speckle technique will be analyzed. The estimated signal-to-noise ratio shows that it seems to be a useful procedure to detect faint objects. Finally, some limitations of the technique and the wavelength choice are discussed.

2. System gain

The technique consists of detecting the probability of zero counts in every pixel of the whole image plane. Deviations of the expected zero-count Probability Distribution will indicate the presence of a planet. The algorithm described by Labeyrie consists of the generation of a dark map by counting, in each pixel, the number of short exposures that contribute zero photons. As these contributions are accumulated in the dark map, a planet’s Airy peak is expected to emerge as a black dot among background noise. To obtain an image, the negative of these results can be displayed. Actually, the planet peak has a size comparable to a speckle and therefore contains several pixels. The optimal value of the number of pixels per speckle, \( j \), to achieve very low-light-level detection, is \( j = 0.62 R/G \), where \( G \) is the system gain [9].

It is possible to develop a simple model to predict the behavior of the Dark Speckle technique applied to an image obtained by a nulling interferometer. Let us consider two identical telescopes observing the same scientific object. In both telescopes the same compensation level is obtained using the corresponding adaptive optics system. Thus, each telescope would produce an image composed of a coherent Airy pattern plus an incoherent speckled halo. The energy at the coherent peak is a factor \( \exp(-\sigma^2_\phi) \) of the total energy [10], where \( \sigma^2_\phi \) is the average residual phase variance in the corrected wavefront, that can be obtained from experimental measurements [11]. The energy at the halo is \( (1-\exp(-\sigma^2_\phi)) \) of the total energy. In these conditions, fields coming from both telescopes are superimposed to produce an interferometric image. The coherent part of the electromagnetic field interferes and the star diffraction pattern vanishes. However the incoherent halo intensities are added, giving a residual halo twice the halo at a single telescope.

The system gain is the key parameter for describing the system performance and for comparing with other techniques. In the nulling interferometer it can be defined as the ratio between the intensity at the core in each of the single telescopes and the residual intensity at the halo of the nulling interferometer. Consequently, the gain provided by the nulling interferometer is the same as the gain between the core and halo in each single telescope [10]:

\[
G_N = \frac{2I_{\text{core TELE}}}{I_{\text{halo NI}}} = \left( \frac{D}{l_c} \right)^2 \frac{\exp(-\sigma^2_\phi)}{\left[1-\exp(-\sigma^2_\phi)\right]} \tag{1}
\]

where \( l_c \) is the correlation length, and is a function of the number of actuators, \( a \), of the compensating system, \( l_c = 0.286 a^{-0.362} D \), and \( (D/l_c)^2 \) is the number of speckles [12]. This is a meaningful gain definition for exoplanet detection, because the planet light does not interfere destructively, as is the case for starlight.

For the task of finding extrasolar planets it is usually considered that the adaptive optics system must at least provide a gain of \( 10^6 \) [13]. In the visible, this value of the gain is
necessary to retain a reasonable value of the number of pixels per speckle $j=0.62\, R/G$ [9]. This need for a high gain value requires the use of a nulling interferometer to suppress the Airy rings, which would otherwise impede the obtention of such a gain value at the planet location.

3. Signal to noise ratio

Up to this point, we have described the system performance through the gain. From now on, the feasibility of the Dark Speckle technique to detect exoplanets is analyzed. The SNR and the integration time required will be estimated.

In order to apply the technique it is necessary to estimate the zero-count probability density due to the scientific object in the interferometric image plane. It follows the Bose-Einstein distribution: $P_{\text{ni}}(0) = (1 + \bar{\kappa})^{-1}$, where $\bar{\kappa}$ is the number of stellar photoevents per pixel and per short exposure. It is interesting to express it as a function of the total photon flux from the star per second, $N_\nu$, which can be related to the star’s magnitude $m_\nu$, the combined quantum efficiency of the optical train and detector $q$, the spectral bandwidth in Angstroms $\Delta \lambda$ and the telescope diameter $D$: $N_\nu = \left(2844 \, 10^{-0.4 m_\nu} \, D \right)^2 \Delta \lambda \, q$. Let $t$ be the short exposure time.

Then, $\bar{\kappa}$ is equal to $t N_\nu \left[1 - \exp\left(-\sigma^2\right)\right]$ divided by the number of pixels, $(D/l_c)^2 * 0.62 \, R/G$. Using Eq. (1), the Bose-Einstein distribution can be written as:

$$P_{\text{ni}}(0) = \left(1 + \frac{tN_\nu}{0.62R} \left[1 - \exp\left(-\sigma^2\right)\right]\right)^{-1}$$

(2)

Now, this technique can be applied to detect a planet close to a star. The probability of zero-counts in pixels without a planet is given by Eq. (2) but in those pixels where a planet appears the zero-count probability is given by $P_{\text{ni}}(0) P_p(0)$, where $P_p(0)$ is the zero-count probability corresponding to the planet. As the Adaptive Optics system provides a high gain, the intensity at the planet PSF core can be considered almost constant. Consequently, the number of photons follows a Poisson distribution. By comparing statistics in pixels with and without a planet, small differences can be detected. The difference function used to detect the planet presence is $D_p = P_{\text{ni}}(0) - P_{\text{ni}}(0) P_p(0)$.

Its SNR can be determined as a function of the number of frames $n$:

$$\text{SNR} = (1 - P_p(0)) \sqrt{n P_{\text{ni}}(0)} = \frac{N_\nu \exp(-\sigma^2)}{R} \sqrt{\frac{tTG}{0.62R + tN_\nu \exp(-\sigma^2)}}$$

(3)

where $T$ is the total integration time. In this equation, it has been taken into account that the planet peak has a size comparable to a speckle and, therefore, contains several pixels, $j=0.62R/G$, which contribute as if they were independent exposures on a single pixel. The dependence of the SNR with the photon flux and with compensation level (through the gain and the residual phase variance) is clear. It is necessary to point out that Eq. (3) represents the behavior of the SNR of the difference function derived for the case of low-light-level. The low-light-level condition means that the probability of detecting zero photocounts in the interferometric image when the star is being detected, $P_{\text{ni}}(0)$, must be close to unity, that actually corresponds to the case when searching for extrasolar planets with a nulling interferometer.

4. Discussion and results
From Eq.(3) the number of frames required to detect a faint companion can be derived. In this analysis, we have considered that diffraction pattern vanishes with nulling, but we have not addressed some of the hard problems that arise in ground-based nulling interferometers to achieve the high gain required, with requisite broadband and dual-polarization. Phase equalization of the paths in the interferometer’s arms must be extremely precise and stable, and amplitudes must also be matched to over 0.1%. Several solutions have been proposed for this task [5], but a thorough analysis of them is beyond the scope of this paper. The technological evolution leads us to the assumption that the interferometer will provide a good enough null [1,5,7].

Furthermore, the choice of the wavelength range in the experiment must previously be discussed. Up to date, commercial photon counting detectors for IR are not available for wavelengths greater than 2 µm. This fact, the longer baseline required to achieve enough resolution and the thermal noise in the devices are drawbacks to detect planets in this wavelength range. Furthermore, the effects from zodiacal and extrazodiacal dust must be considered. Nevertheless, there would be some advantages too, such as the better brightness ratio or the better Fried parameter. Currently, we propose the first experiments to be made in the visible range. However, as soon as photon counting detectors for IR wavelengths are developed, the use of the nulling interferometer in IR wavelengths should become a powerful tool for observations both in ground-based and in space-based next generation interferometers.

For visible wavelengths \( r_0 \) is rarely greater than 20 cm. If a 10 m telescope assisted by an adaptive optics system with \( 10^4 \) actuators is considered, a \( 10^6 \) gain could be achieved, provided scintillation effects are compensated. This condition on the gain stresses current technology to its limits. The star photon flux per second at this aperture is \( 10^{10} \) ph/s taking \( q=0.2, \) 100 nm bandwidth and \( m=3 \). As a consequence, to obtain a \( \Delta \text{SNR}=5 \), with typical values of exposure time of 20 ms, and contrast ratio \( 10^9 \), a total integration time of 3.2 hours is necessary.

In the IR case, for a detection wavelength between 5 and 10 µm the size of the Fried parameter is typically between 3 and 7 m. Hence, it is much easier to build an adaptive optics system with the desired \( 10^6 \) gain. If a bandwidth of 1µm is used, the number of detected photoelectrons from the star is \( 10^{12} \) ph/s. Furthermore, the brightness ratio in the IR is typically smaller than in visible wavelengths. Consequently, the total integration time would be dramatically reduced. However, the actual integration time would be increased because of the thermal noise in the devices and noise from the zodiacal dust. We consider extrazodiacal dust effects negligible, because models of formation of the solar system show that systems with much less dust than ours can be expected, although it would be an important error source for most planetary systems. In spite of these problems, the achievable goals are so relevant, that a great effort to prepare the Dark Speckle technique in the IR should be developed as soon as photon counting detectors are available for wavelengths between 5 and 10 µm.

Figure 1 shows the integration time as a function of the compensation level used to estimate the zero-count statistics. There are two curves corresponding to different values of \( D/r_0 \). It shows that the combination of the nulling interferometer and the Dark Speckle technique could soon (in the next two decades) allow the ground-based imaging of exoplanets either in the visible, if the technological challenges to achieve the required high gain are solved, or in the IR, if photon-counting detectors for this range of wavelengths are developed and thermal noises can be controlled.

5. Conclusion

We have shown that cancellation of the star diffraction pattern is required to apply the Dark Speckle technique to direct imaging of exoplanets. From a simple model for the energy distribution in partially compensated images, we have analyzed the behavior of this Speckle technique in a ground-based nulling interferometer assisted by adaptive optics. We conclude that combination of the nulling interferometer and the Dark Speckle technique would allow...
the ground-based imaging of exoplanets either in the visible, if the technological challenges to achieve the required high gain are solved, or in the IR, if photon-counting detectors for this range of wavelengths are developed.

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Fig. 1. Integration time necessary to obtain a SNR=5 as a function of the number of actuators in each adaptive optics system, if the diameter of both telescopes is 10 m and with a total flux from the star of $10^{10}$ ph/s. The exposure time is 20 ms. The solid curve corresponds to values of $R=10^9$ and $D/r_0=50$ (visible wavelengths) and the dashed blue curve to value of $R=5 \times 10^8$ and $D/r_0=2$ (mid IR).