Recent Coronagraph Experimental Studies

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ABSTRACT

Some activities on coronagraph experiments in Japan are reported. One is pre-optics for dynamic range absorption with nulling interferometer and deformable mirrors by Nishikawa et al. in NAOJ. Another is polarization differential imaging by Baba et al. in Hokkaido Univ. The third is common-path achromatic interferometer coronagraph by Tavrov et al. in NAOJ and TUAT.

Dynamic range absorption by nulling interferometer and AO

A new technique for very precise wavefront error reduction is now under study by Nishikawa et al.[1,2], and similar works are reported before[3-6]. The technique uses an unbalanced nulling interferometer (UNI) and phase and amplitude correction (PAC) by an AO system with a normal wavefront sensor and two deformable mirrors. The UNI+PAC is used as pre-optics of a coronagraph (Fig. 1). The pre-optics can absorb 10^2 dynamic range and the downstream coronagraph provides 10^8 for the total contrast which can be achieved by $\lambda/1000$ optics.

A brief description of the principle is as follows. The UNI for two beams provides some order of extinction of the central star light. Since the wavefront of the UNI output has still enough large amplitude without phase singularity and wavefront errors are artificially magnified by the extinction ratio, a normal wavefront sensor and two deformable mirrors can be applied for the PAC. After the wavefront error correction at the error-magnified stage, the wavefront error is the same level as the initial wavefront but the star light is reduced. In the image plane, after the UNI-PAC method is applied, the peak intensity of the central star is dimmed and speckle noise level is also reduced relative to off-axis planet intensity (Fig. 2).

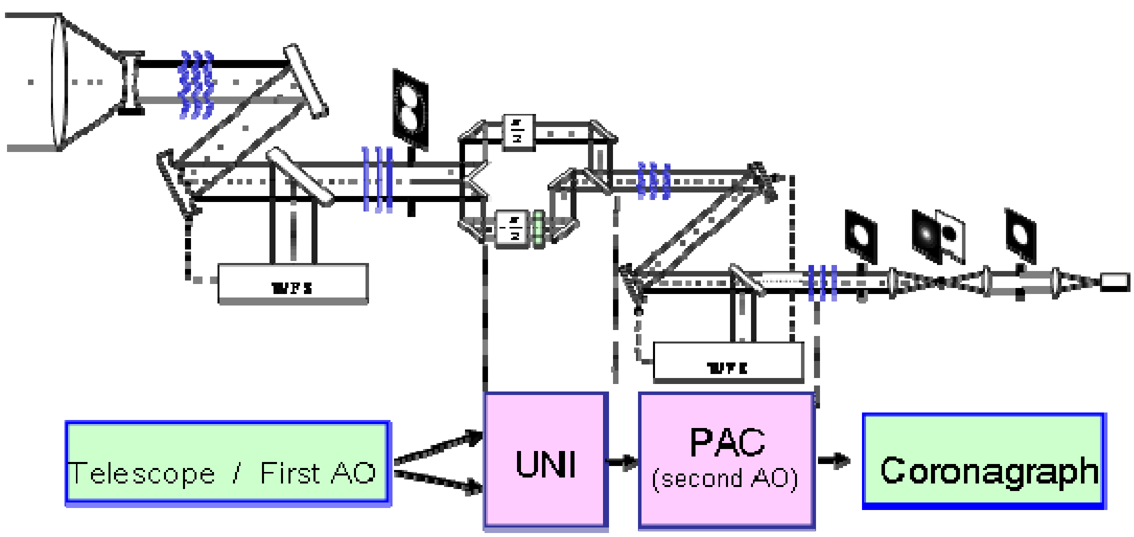


Figure 1. *A coronagraph configuration including the UNI+PAC method. The wavefront errors are magnified at UNI and corrected at PAC and its output light is led to a coronagraph.*

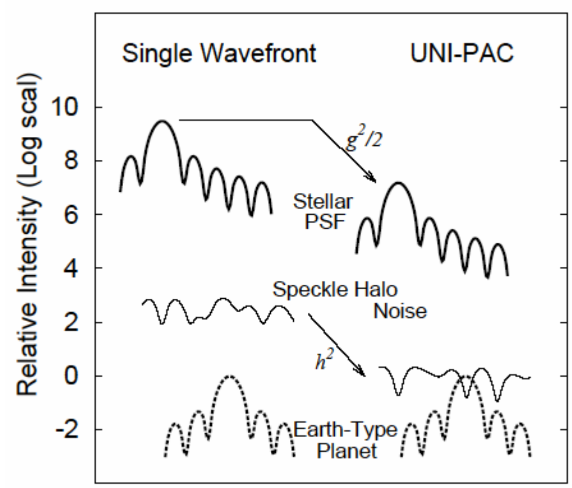
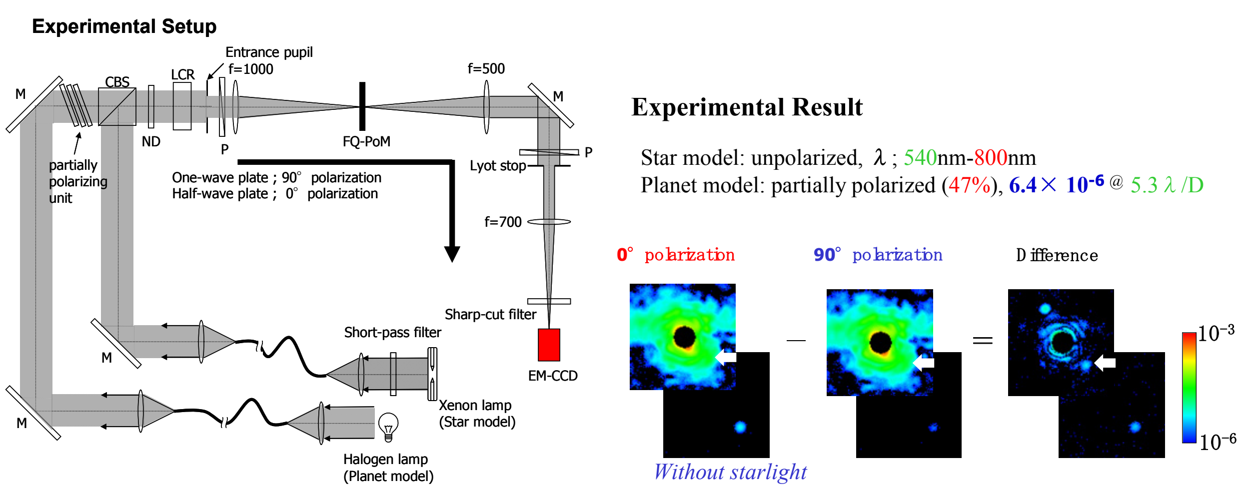


Figure 2. *Pre-optical effects by UNI+PAC in the image plane.*

The UNI-PAC method can be applied to two collimated beams at some styles of telescope configurations in front of various kinds of coronagraphs or interferometric nulling optics. Possible telescope architectures are: (a) Long Baseline Interferometer, (b) (Large) Single Telescope, Sub-aperture Interferometer, (c) Off-axis Single Telescope, Overlapped Sub-Aperture Interferometer, (d) Single Telescope, Rotation Shearing Interferometer. The multiple use of the UNI-PAC processes may be also possible for more than four telescope beams or VNC-like architecture. In this case the central star will be dimmed by 1E-4 but still the wavefront is compensated to the AO limit, where a coronagraph with a dynamic range of 1E6 would be used as a final stage. Note that we do not make detailed consideration on the use of various architectures, yet.

Polarization differential imaging with four-quadrant polarization mask

Baba et al. have been making experiments of some polarization applications with white light, a nulling interferometer using geometric (Pancharatnam) phase, a FQPM coronagraph with a liquid crystal, and so on[7–14]. A polarization differential imaging result is obtained by Sato, Murakami, and Baba, in which a partially polarized planet model light of 10^6 contrast at 5λ/D is observed using very wide band light of 540nm–800nm. The aim is to extract exoplanet image from speckle noise, and the method is a nulling stellar coronagraph with a four-quadrant polarization mask using a characteristics of the light from exoplanet is expected to be partially polarized, while speckle noises are caused by unpolarized stellar light.



Recent development of achromatic interfero-coronagraph for planet finder: practical and theoretical limits have become equal

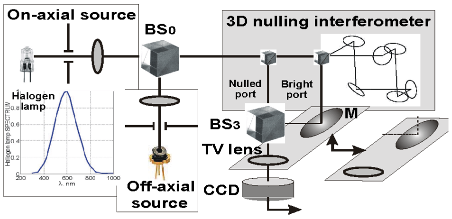


__Figure 3.__ General experiment schematic.

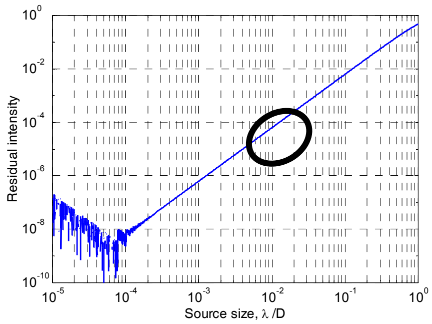


__Figure 4.__ Not nulled residual intensity. AIC scope in circle.

(a) **(b)**

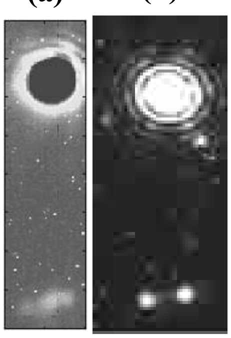


__Figure 5.__ Bright result up. Nulling results on bottom. (a) – 300 nm broadband light; (b) – He-Ne laser light.

A three-dimensional common-path interferometer is proposed[15–17], which can achromatically null out an on-axis source, while maintaining the detectability of an off-axis source (Fig. 3). Geometric phase in the three-dimensional interferometer introduces an achromatic π-phase shift to the light from the on-axis source, such that destructive interference nulls out the axial light at one of the ports of the interferometer. Light from the off-axis source, which is exempt from the π -phase shift, comes out from both ports with equal intensity. The common-path scheme makes the system highly immune to environmental disturbances. In the described experiment, a 10^{-4} peak-to-peak nulling contrast was obtained for spatially unfiltered image and 10^{-5} with spatial filter.

The best approach to date is to interferometrically null the star's output while letting the planet's light shine through. We have developed an achromatic interferometer-coronagraph for extrasolar-planet detection that has a common path to allow stable operation under nonideal conditions[1]. The 180° rotational-shearing interferometer, which has a 3-D path and is a modified Sagnac interferometer, introduces a geometrical π phase shift for an on-axis source, nulling the source.

The stellar disc is resolved by a telescope as an incoherent extended source, and an incomplete nulling has a residual intensity versus the angular extend of the stellar disc, which dependence is shown in Figure 4.

By a laser light, Figure 5. it can be nulled out just perfectly being limited only by the instrument error, which we studied. In the *Nulled* area, shown in Figure 6, the residual light forms a partially developed speckle field. It has the peak-to-peak intensity of 9×10^{-5} in respect to to the *Bright* area intensity.

In Figure 6, the *Bright* signal is shown in 10^3 times attenuated by neutral density filter. We consider that the intensity modulation being observed as the partially developed speckles is originated from the wavefront modulations, which caused by the reflections on $_{BB}$ mirrors, whose actual surface figures depart from an ideal plane. Since the reflective surface figures depart from a perfect plane by the order of wavelength fractions, we have to consider this factor as the main instrumental error in the present demonstrator. Therefore, a spatial filter being implemented by a pinhole can sufficiently improve the nulling contrast, by our experiment down to 9×10^{-6}. The measured dependence of the nulling contrast on the optical axis tilt is shown in Figure 7. Hence all the optical methods are limited by the same kind aberrations caused by optics imperfection, new differential techniques improve the nulling contrast to fit the required range of 10^{-6} in infrared and to 10^{-9} in visible. These techniques have important advances if they are used with our achromatic coronagraph.

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[1] A. Tavrov, Y. Kobayashi, Y. Tanaka, T. Shioda, Y. Otani, T. Kurokawa, and M. Takeda, "Common-path achromatic interferometer-coronagraph: nulling of polychromatic light" Opt. Lett. **30**, 2224, (2005).

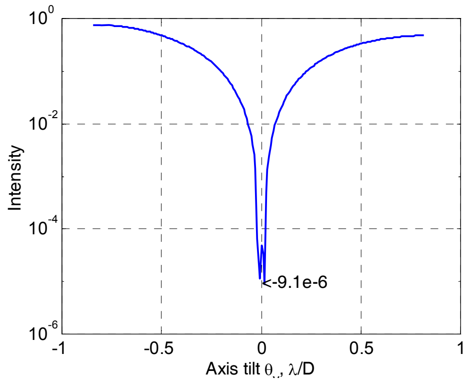

Figure 6. *Nulling in image plane.*

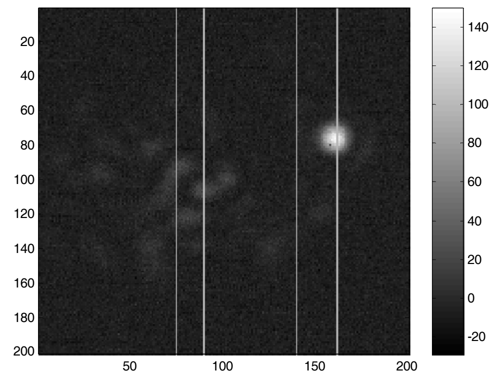

Figure 7. *Spatial filter used.*

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