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Combination of nulling interferometer, nulling coronagraph, and modified pupil method

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Abstract. We investigated two-stage combinations from three methods, nulling interferometer, nulling coronagraph, and modified pupil, calculating reduced intensity profile of a resolved central star and transmission for exo-planets. An achievable dynamic range can be derived by dividing the residual halo intensity of the star by the transmitted peak intensity of the planet. For observation parameters, here assumed are the wavelength of 600 nm in optical and the telescope diameter of 3 m. The combination of the nulling interferometer and the four-quadrant phase mask coronagraph showed the best performance reaching to 10^{-10} dynamic range at 100mas distance from the central star among five candidates of combination using nulling interferometer, achromatic interfero-coronagraph, four-quadrant phase mask, and shaped pupil method.

Keywords. instrumentation: interferometers, techniques: interferometric, techniques: image processing, telescopes, stars: imaging, planetary systems.

1. Introduction

Three methods are well known of achieving high dynamic range observations especially for the direct detection of extra-solar planets, nulling interferometer, nulling coronagraph, and modified pupil method. We investigate their combinations focusing on a light suppression for a resolved central star and a transmission for a planet detection area.

The nulling interferometer can achieve the perfect null at an on-axis point source but remains light for off-axis ray which dependence is a square of the angle for a two-phase nulling condition. The nulling interferometer can be considered as pre-optics producing weakened flat wave fronts, combined with any downstream single telescope method as seen in Nishikawa *et al.* (2005). Nulling coronagraphs (AIC: achromatic interfero coronagraph, e.g. Baudoz *et al.* 2000, FQPM: four quadrant phase mask coronagraph, e.g. Rouan *et al.* 2000) are also useful as pre-optics though they produce non-flat wave fronts. Modified pupil (apodization or SP: shaped pupil, e.g. Kasdin *et al.* 2003) can reduce halo intensity having an insensitive characteristics to the size of a resolved star, but in many cases the PSF (point spread function) core radius increases hiding close planets. The modified pupil method is used at the entrance of the optics and also at the Lyot stop. All of the methods reduce throughput for planets instead of the high dynamic range. In the present paper, we examined five cases of the combinations.

2. Calculation

We calculate the residual halo intensity of a resolved star and the transmission at its sorrounding area. In this paper, we assume observation parameters as follows, the wavelength λ of 600 nm, the telescope diameter D of 3 m, the baseline for NIB (nulling

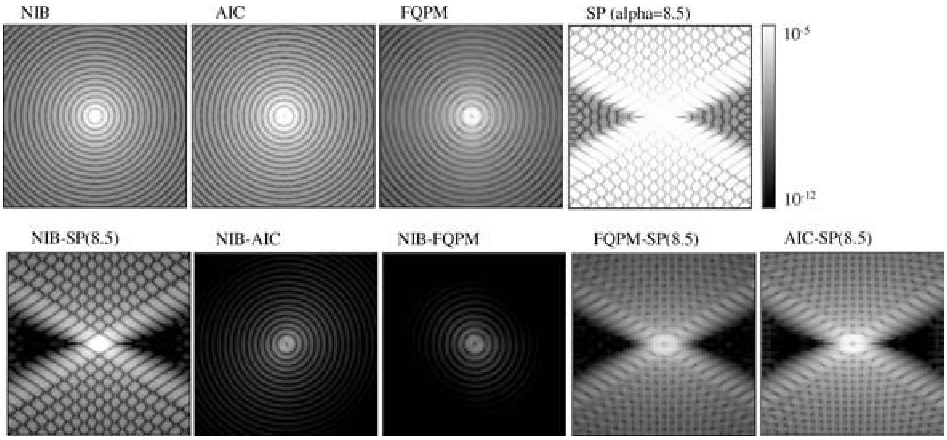

Figure 1. The central star images processed by high dynamic range methods of (upper) single way and (lower) combination of them. The central star diameter is assumed to be 0.02 λ/D, where the telescope diameter is 3m and the wavelength is 600nm. NIB: nulling interferometer in Bracewell's configuration with a baseline length of 3m, AIC: achromatic interfero coronagraph, FQPM: four quadrant phase mask coronagraph, SP: shaped aperture with $p(x) = I_0\left(\alpha\sqrt{1-x^2}\right)/I_0(\alpha)$ and $\alpha = 8.5$ used as an approximated prolate function, here I_0 is the zero-order modified Bessel function of the first kind. Lyot stop of 90% diameter is used for FQPM.

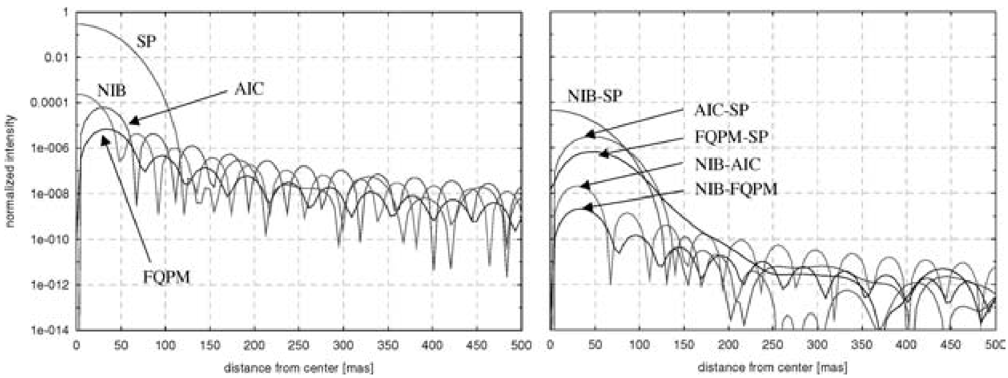

Figure 2. Radial profiles of the central star images along x-axis processed by high dynamic range methods of (left) single method and (right) combination of them, for the same parameters of Fig. 1. The central star diameter of 0.02 λ/D assumed here corresponds to 0.83 mas (equivalent to the Sun from 11.2 pc distance) and an Earth-like planet would be seen at 88mas. A combination of NIB-FQPM is the best reaching to 10^{-9} at 88mas, and also NIB-AIC. All of the combinations show reduced intensity of the central star lower than the original single method profiles and 10^{-10} farther than 2AU position.

interferometer of Bracewell's configuration) is 3 m, and the central star diameter is 0.02 λ/D (0.83 mas, equivalent to the Sun at 11.2 pc distance, then an Earth-like planet would be seen at 2.1λ/D or 88mas). The star images processed by high dynamic range methods in single way (NIB, AIC, FQPM, and SP) and combination of them (NIB-SP, NIB-AIC, NIB-FQPM, FQPM-SP, and AIC-SP) are calculated and shown in Fig. 1, and radial profiles of the images along x-axis are shown in Fig. 2. A shaped pupil is set by using

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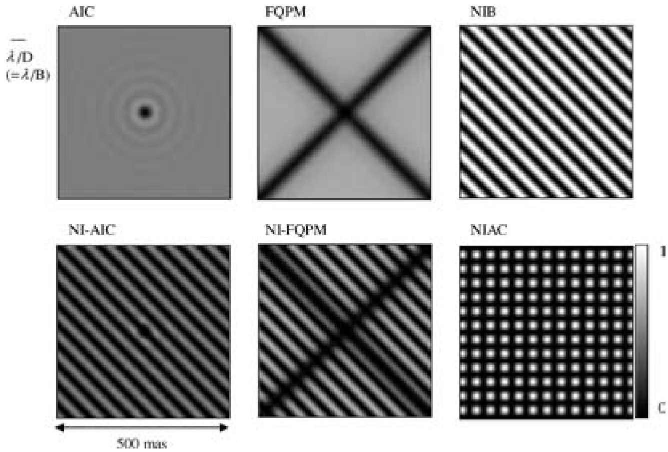

Figure 3. Transmission maps for the single and the combination methods. Maximum intensity of the images are used to estimate these maps.

an approximated prolate function as described in the figure caption. A combinations of NIB-FQPM is the best reaching to 10^{-10} at the Earth position, and NIB-AIC is also good. All of the combinations show reduced intensity of the central star lower than the original single method profiles and 10^{-10} farther than 2AU distance.

Residual intensity of dual-phase nulling methods has a square dependence on spatial size of a resolved star, and a forth-order law is seen for their double combination, which is similar to a four-aperture nulling interferometer of Angel's cross (NIAC: e.g., Dubovitsky & Lay 2004) or interferometric nulling coronagraph (Levine *et al.* 2003).

Possible combinations, configurations and parameters are not perfectly searched, here. The shaped pupil can be exchanged by a phase induced amplitude apodization (Guyon 2003). The two-telescope interferometer baseline can be reduced more using a Mach-Zehnder interferometer described as a visible nulling coronagraph (Levine *et al.* 2003). There is a possibility to achieve higher dynamic range than shown here even by a dual-stage combination when conditions are well-examined. We should note that, however, tip-tilt errors and wavefront errors are not considered here.

3. Transmission for planet and achievable dynamic range

Planet light is affected by the nulling or the apodization methods reducing the total energy and/or the peak intensity by diffusing the PSF. Transmission maps (here, maximum intensity of the images are used to estimate) for NIB, AIC and FQPM are shown in Fig. 3. as well as the combinations of NIB-AIC and NIB-FQPM, where that of NIAC is shown for comparison. The shaped pupil method has a constant value 0.29 of transmission in the field of view, which is the peak of the SP's profile in Fig. 2 (left). In Fig. 4, azimuthally averaged transmission profiles are plotted for the single and the combination methods. The transmission profiles are almost 0.2 for all of the combinations we considered under the present conditions.

The final achievable dynamic range would be derived by dividing the resolved star image profiles by the transmission profiles, so that multiplying a factor of about 5 is enough to consider the final result looking at the resolved star image profiles in Fig. 2 (right).

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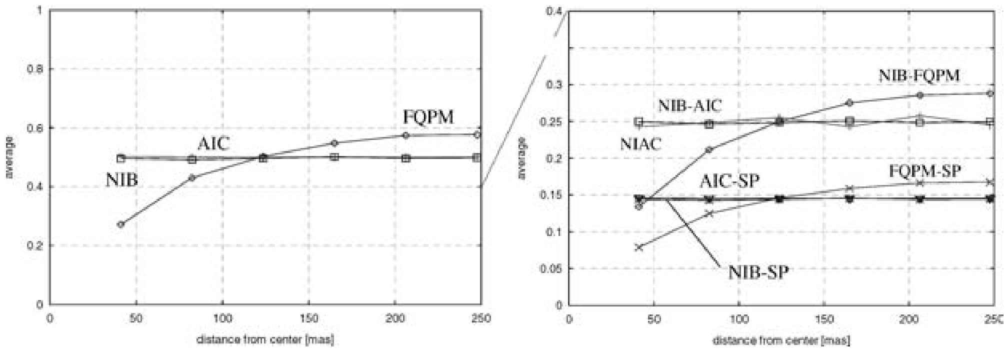

Figure 4. Radial profiles of azimuthally averaged transmission maps of Fig. 1 for the single and combination methods. Here a constant value of transmission for SP is used, the central peak value of PSF seen in Fig. 2. The resolved star image intensity profiles in Fig. 2 should be divided by these profiles to know achievable dynamic range. However, the transmission profiles are found to be about 0.2 for all of the combinations.

4. Conclusions

We investigated some combinations of high dynamic range methods. A two-stage combination of the nulling interferometer and the four-quadrant phase mask coronagraph showed the best performance among the candidates under the 600nm dual 3m-telescope conditions reaching to 10^{-10} dynamic range at 100mas distance from the central star whose diameter is 0.02 λ/D. There is a possibility to achieve higher dynamic range than shown here with other well-examined dual-stage combinations, when errors from tip-tilt and wavefront shape are not significant.

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References

Baudoz, P., Rabbia, Y., & Gay, J. 2000, *A&AS*, 141, 319

Dubovitsky, S. & Lay, O. P. 2003, *Proc. of SPIE* 5491, 284

Guyon, O. 2003, *A&A* 404, 379

Kasdin, J. N., Vanderbei, R. J., Spergel, D. N., & Littman, M. G. 2003, *ApJ*, 582, 1147

Levine, B. M., Shao, Michael, Liu, Duncan T., Wallace, James K. Lane, & Benjamin F. 2003, *Proc. of SPIE* 5170, 200

Nishikawa, J., Kotani, T., Murakami, N., Baba, N., Itho, Y., & Tamura, M. 2005, *A&A* 435, 379

Rouan, D., Riaud, P., Boccaletti, A., Clenet, Y., & Labeyrie, A. 2000, *Publ. Astron. Soc. Pacific*, 112, 1479