

International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny



The evanescent wave coronagraph project: development status and potential for space based observations

Mary Angelie Alagao

Christophe Buisset

Thierry Lépine

Eric Thiébaud

et al.



icso proceedings



The Evanescent Wave coronagraph project: development status and potential for space-based observations

Mary Angelie Alagao^{*,a}, Christophe Buisset^a, Thierry Lépine^{b,c}, Eric Thiébaud^d, Maud Langlois^d, Michel Tallon^d, Isabelle Tallon-Bosc^d, Yves Rabbia^e, Saran Poshyachinda^a, Boonrucksar Soonthornthum^a

^aNational Astronomical Research Institute of Thailand (NARIT), 260 Moo 4, T. Donkaew, A. Maerim, Chiangmai, 50180, Thailand; ^bInstitut d'Optique Graduate School, 18 rue Benoît Luras, 42000 Saint-Etienne, France; ^cLaboratoire Hubert Curien, Université de Lyon, CNRS, 18 rue Benoît Luras F-42000, Saint-Etienne, France; ^dUniv Lyon, Univ Lyon1, Ens de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France; ^eLaboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Boulevard de l'Observatoire, CS 34229, 06304 Nice Cedex 4, France

ABSTRACT

The Evanescent Wave Coronagraph (EvWaCo) is a coronagraph with an occulting mask based on the frustration of total internal reflection to i) produce an achromatic extinction of the central star and ii) reveal the faint companion surrounding the star. Results obtained in laboratory conditions show contrast performance of a few 10^{-6} between $10 \lambda_C/D$ and $20 \lambda_C/D$ over the full I-band centered at the wavelength $\lambda_C = 800$ nm with a spectral ratio of $\Delta\lambda/\lambda_C \approx 20\%$ in unpolarized light.

In this paper, we discuss the advantages of using EvWaCo to observe and characterize exoplanets with a space-based telescope. In the first section, we describe the system and present the current results obtained with the EvWaCo testbed. We also illustrate the capability of this coronagraph to detect the companion 30,000 times (respectively, 100,000 times) fainter than the central star at distances equal to 15 Airy radii (respectively, 30 Airy radii) from the PSF center in polychromatic and unpolarized light.

In the second section, we describe the design of the prototype dedicated to the on-sky tests of the instrument with the 2.4 m Thai National Telescope at horizon 2020. This prototype has been designed with the objective to reach a contrast equal to a few 10^{-4} at the inner working angle (IWA) equal to $3 \lambda/D$ from the star PSF center while observing through the atmosphere over the full photometric I-band. This prototype will include an adaptive optics specified to reach at $\lambda \approx 800$ nm a Strehl ratio > 0.8 for magnitude $m < 7$.

In the third section, we show the theoretical performance of EvWaCo: a contrast comprised between a few 10^{-6} and 10^{-7} in the I-Band between $3 \lambda/D$ and $10 \lambda/D$ in the I-Band for an IWA equal to $3 \lambda/D$ with a Gaussian apodization in unpolarized light. We also show that similar contrasts performance are obtained in the V-, R-, bands, thus illustrating the EvWaCo quasi-achromaticity. Finally, we discuss the advantages and the limitation using the proposed concept for space-based observations and spectral characterization of exoplanets.

Keywords: Coronagraphy, Adaptive Optics, Exoplanets, High Angular Resolution, Evanescent Wave, Tunneling effect.

*angelie@narit.or.th; phone +66 6 3170 4607; www.narit.or.th

1. INTRODUCTION

The National Astronomical Research Institute of Thailand is collaborating with the Institut d'Optique Graduate School (IOGS), the Laboratoire Hubert Curien (LabHC), the Centre de Recherche Astrophysique de Lyon (CRAL), and the Université Côte d'Azur to develop a new kind of compact and cost-effective coronagraph called the Evanescent Wave Coronagraph (EvWaCo). The focal plane mask (FPM) involves the frustration of total internal reflection [2] (FTIR) to suppress the central star light. We showed in the previous communication [3] that the mask has a quasi-Gaussian transmission and is achromatic such that its size varies linearly with wavelength.

The schematic of the proposed coronagraph is shown in Figure 1. The output beam coming from the telescope is collimated and is reflected by a deformable mirror (DM) toward the lens L1 that focuses the beam on the hypotenuse of the Focal Plane Mask FPM. This FPM is composed of a prism placed in contact with the convex diopter of a plano-convex lens [3]. On the star channel, the on-axis beam is transmitted by the FPM due to the frustration of the total internal reflection (FTIR). The beam is then collimated by the lens L4 and transmitted toward the wavefront sensor WFS. On the companion channel, the off-axis beam incident on the FPM is totally reflected towards the lens L2 that collimates this beam toward the Lyot stop LS. Finally, the beam transmitted by LS is focused on a detector by the lens L3. In this system, the output of the WFS feeds the adaptive optics (AO) control loop to compensate for the wavefront distortions induced by the manufacturing errors, the thermo-elastic effects, the vibrations and the zero gravity effect.

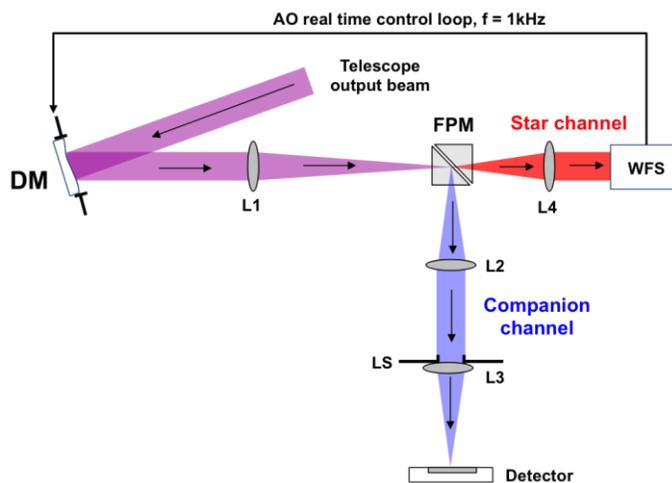


Figure 1. Evanescent wave coronagraph with adaptive optics

This paper is organized as follows: Section 2 describes the contrast measurements obtained using the testbed at NARIT over the full I-band centered at the wavelength $\lambda_c = 800$ nm with a spectral ratio $\Delta\lambda/\lambda_c \approx 20\%$ in unpolarized light. In particular, we present the results of the detection of a faint companion located at $15 \lambda/D$ and $30 \lambda/D$ from the star center performed in laboratory conditions. In Section 3, we describe the design of the EvWaCo prototype that will be placed at the 2.4 m Thai National Telescope (TNT) with the aim to measure a contrast equal to a few 10^{-4} at an IWA equal to $3 \lambda/D$ during on-sky observations. Finally, we present in Section 4 the theoretical performance of a version of EvWaCo optimized for the space applications in the V-, R- and I-bands. We show in this section that the proposed concept could reach i) IWA values slightly varying from $3 \lambda/D$ in the I-Band to $5 \lambda/D$ in the V-Band and ii) a contrast varying between a few 10^{-6} to a few 10^{-7} at distances comprised between the IWA and $10 \lambda/D$ over these 3 photometric bands. Finally, we discuss the advantages and the limitations of EvWaCo for space-based applications.

2. EVWACO TESTBED PERFORMANCE

In 2016, NARIT and IOGS/LabHC have developed a testbed to demonstrate the concept of EvWaCo. This testbed has been presented in previous communication [3][4][5] and is similar to the schematic presented in Figure 1. The only difference is that the DM is replaced by a plane mirror. The results presented in this section have, thus, been obtained without adaptive optics.

Figure 2 shows the irradiance distribution of the star and a companion that is 3.10^4 fainter at $15 \lambda_c/D$ (top panel), and 10^5 fainter at $30 \lambda_c/D$ from the star PSF center (bottom panel). During these measurements, the star source emits an unpolarized light over the Johnson-Cousins photometric I-band which is centered on the wavelength $\lambda_c \approx 800$ nm with a spectral ratio $\Delta\lambda/\lambda_c \approx 20\%$ [5]. The companion source is a LED emitting at the wavelength $\lambda = 780$ nm with a spectral ratio $\Delta\lambda/\lambda_c \approx 3\%$. These measurements have been obtained in unpolarized light using a Lyot stop diameter equal to 78% of the exit pupil diameter, thus yielding a system throughput equal to 60%.

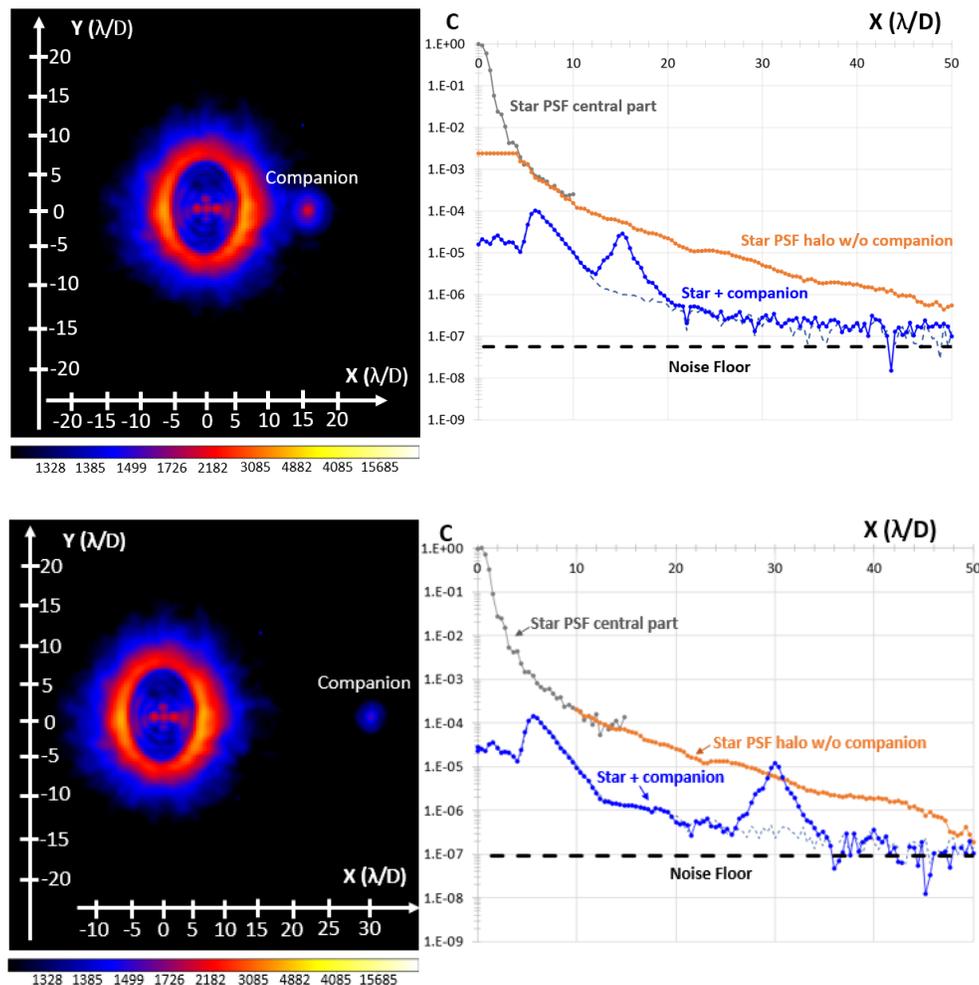


Figure 2: Irradiance distributions and cross-sections of the star and its companion obtained over the full I-band for a spectral ratio $\Delta\lambda/\lambda_c \approx 20\%$ in unpolarized light: (top) the star PSF centered on the mask while the companion, 3.10^4 fainter than the star, is located at $15 \lambda_c/D$, and (bottom) the star PSF is centered on the mask while the companion, 10^5 fainter than the star, is located at $30 \lambda_c/D$. The images shown are a median of 101 images obtained with an integration time of 1.5 seconds per image. We have verified from previous measurements that the mask transmission at the distances $15 \lambda_c/D$ and $30 \lambda_c/D$ is equal to unity.

The contrast measured without the companion, represented by the blue dotted curve, varies between 10^{-5} to a few 10^{-7} over the distances $10 \lambda_C/D$ to $25 \lambda_C/D$ from the star PSF center. Between $25 \lambda_C/D$ and $35 \lambda_C/D$, the contrast is equal to a few 10^{-7} from the star PSF center.

We notice that in the case of a companion 30,000 fainter than the central star and located at $15 \lambda_C/D$ from the star PSF center (respectively, 100,000 fainter than the central star and located at $30 \lambda_C/D$), the companion is clearly detected by the setup with a very good signal-to-noise ratio (SNR). These results illustrate the capability of the coronagraph in its current status (quasi-diffracted limited regime in a controlled environment, without adaptive optics and without central obscuration) to detect a companion over the full I-band.

3. PROTOTYPE DESIGN AND THEORETICAL PERFORMANCE

Table 1 shows the optical performance specified for the prototype currently under development that will be tested on an unobstructed sub-aperture of the Thai National Telescope. The entrance pupil of the prototype will be an ellipse with a major axis (D_{maj}) of 1 m and a minor axis (D_{min}) of 0.7 m. The choice for the shape of the entrance pupil has been adjusted to make sure that the geometry of the PSF will fit the geometry of the coronagraphic mask. The science channel will operate in the I-band following the current testbed conditions of contrast measurements. The plate scale will be equal to $0.08''/\text{pixels}$ and the Field of View (FOV) will be a square of extension equal to $2'' \times 2''$. The measurements of the wavefront errors with the WFS will be performed on the star channel over the spectral bands V-, R-, and I-bands.

The AO loop will operate at a frequency higher than 1 kHz and will provide a Strehl ratio higher than 0.8 for magnitudes brighter than $m_v = 7$ and under a seeing of $\theta \approx 1''$. The AO loop has been specified to be able to close under seeing conditions as high as $\theta \approx 2''$. The deformable mirror (DM) will have a clear aperture equal to 21 mm and will comprise 14 actuators along the pupil diameter. The AO control radius will thus be equal to $7 \lambda/D$. The WFS is specified to have 13×13 microlenses and the WFS detector will provide at least 7 pixels per micro lens PSF. A full description of the adaptive optics specifications can be found in [5].

The optical design of the prototype mounted on the TNT instrument cube (left panel) and a detailed diagram of the EvwaCo prototype (right panel) are shown in Figure 3. The TNT is a Ritchey-Chretien telescope composed of two hyperbolic mirrors M1 and M2, and two plane mirrors M3 and M4 that directs the beam toward the Nasmyth cube. The off-axis parabola OAP1 collimates the beam reflected by M4, and the tip-tilt mirror TTM reflects the beam toward the apodizer APO. The beam transmitted by the apodizer is reflected by the deformable mirror DM towards the off-axis parabola OAP2 that focuses the beam toward the FPM.

The folding mirror FM2 reflects the beam transmitted by the FPM towards the WFS. This constitutes the star channel. The companion channel comprises the off-axis parabola OAP3 that collimates the beam reflected by the FPM towards the folding mirror FM1. Then, FM1 reflects the beam towards the Lyot stop placed in the exit pupil plane. Finally, the beam transmitted by the Lyot stop is focused on the scientific camera by the lens L1.

The aperture stop AS is a mask with an elliptical aperture (not represented in the layout) placed on the DM. This mask is imaged on M1 by OAP1 and M2. The image of the AS on M1 serves as the entrance pupil of the system which is an ellipse with a major axis $D_{maj} = 1$ m and a minor axis $D_{min} = 0.7$ m. The AS is imaged on the Lyot stop plane by the OAP2 and OAP3.

NARIT is currently developing the mechanical design for the focal plane mask that includes a system that can accurately control the pressure between the mask and the lens, thus, allowing the IWA to be finely and continuously tuned during observations. This upgraded version of the FPM will be tested in the beginning of the year 2019.

Table 1. Optical performance specifications

Parameter	Specification	Comments
Science channel nominal spectral band	I-Band	Current Spectral band for demonstration of EvWaCo performance.
WFS Spectral band	[450 nm, 900 nm]	Enlarged with respect to Science beam spectral band to increase WFS SNR, limited by coronagraphic mask AR coating.
Entrance Pupil shape and size	Elliptical, major axis: 1 m, minor axis:0.7 m	Elliptical shape selected to provide an elliptical PSF which fits the FPM geometry. Major axis dimensions: maximum dimension to use a sub-pupil of the TNT without central obscuration
TNT sup-pupil aperture number	24	$F\# = \text{TNT focal} / \text{entrance pupil major axis}$
Aperture number of the beam incident of the Focal Plane Mask	$F\#_{\text{FPM}} = 32$	Optimization of chromatic effects [3]
Raw contrast	$< 10^{-4}$ at IWA location	Limited by wavefront high frequency errors
Inner Working Angle	$< 3 \lambda/D$ at $\lambda = 800 \text{ nm}$	Small-angle coronagraph requirement [9]
Adaptive optics Control radius	$7 \lambda/D$ at $\lambda = 800 \text{ nm}$	Polishing error dominant a distances greater than $7 \lambda/D$
FOV	$2'' \times 2''$	AO active area
Plate scale	$0.08''$	2 pixels per element of resolution λ/D

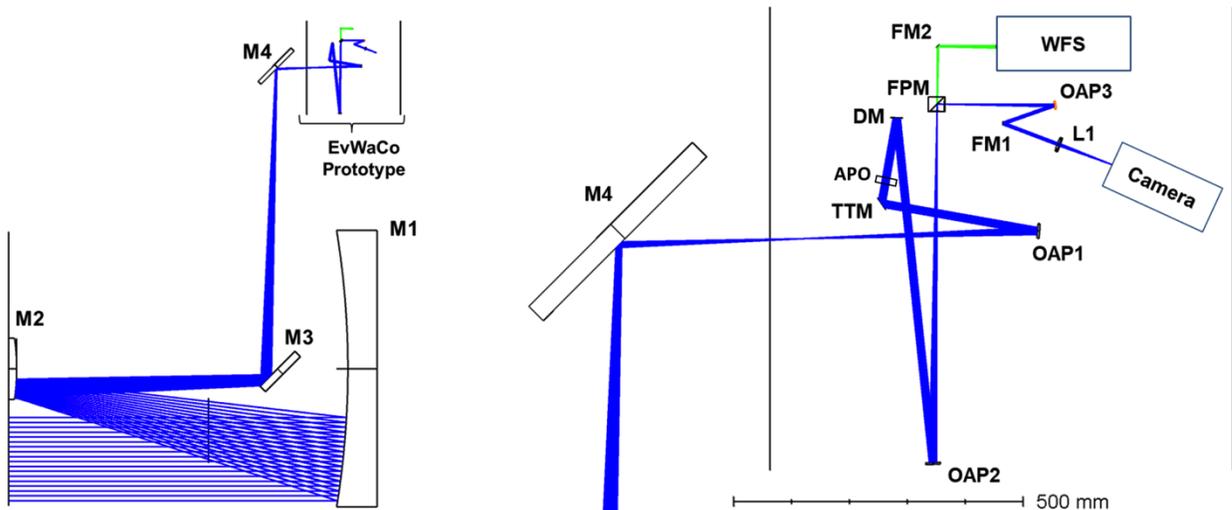


Figure 3. Left: ZEMAX view of EvWaCo mounted on the TNT. Right: close-view of the EvWaCo prototype. The full name of the acronyms are as follows: off-axis parabola OAP, tip-tilt mirror TTM, apodizer APO, deformable mirror DM, focal plane mask FPM, folding mirror FM, wavefront sensor WFS.

4. EVWACO POTENTIAL FOR SPACE-BASED APPLICATION

4.1 Theoretical Contrast Performance

We have developed a model of the EvWaCo companion channel to calculate the irradiance distribution in the image plane and the pupil planes by performing a succession of Fast Fourier Transforms. This model has been fully described in a previous communication [5]. In this section, we present the theoretical performance of EvWaCo obtained with the following assumptions: i) the IWA is equal to $3 \lambda/D$, ii) the pupil is elliptical and apodized with a Gaussian function of Full Width at Half Maximum (FWHM) adjusted to reach a transmission equal to 5% at the edges of the pupil and iii) Lyot stop diameter equal to 78% of the exit pupil diameter.

Figure 4 shows the normalized transmission of the EvWaCo entrance pupil with an apodizer placed after the aperture stop and the calculated theoretical performance in diffraction-limited regime is shown in Figure 5. We notice that at the location of the IWA $\approx 3 \lambda c/D_{maj}$ in the I-band, the raw contrast is equal to $2 \cdot 10^{-6}$. At a distance between the IWA and $10 \lambda c/D_{maj}$, the raw contrast is equal to a few 10^{-7} . We also notice that the apodizer improves the contrast by approximately one order of magnitude.

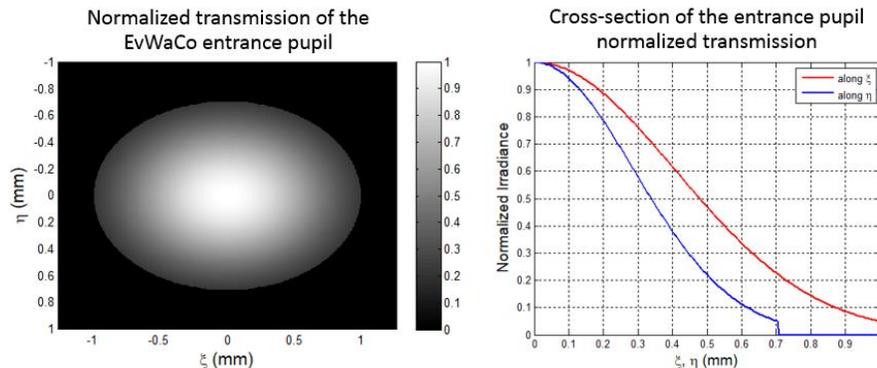


Figure 4. Normalized transmission of the apodizer placed after the aperture stop. The value of the normalized irradiance distribution at the pupil edges is 5% along the ξ - and η -axes.

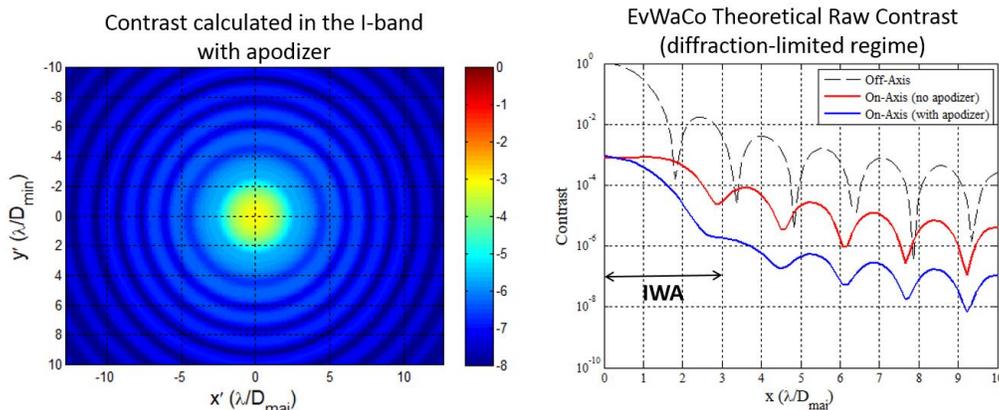


Figure 5. Left: star residual irradiance distribution represented in log scale for a contrast obtained over the full I-band in unpolarized light with apodizer placed after the aperture stop. Right: cross-section along the x-axis of an off-axis PSF (black dotted curve), on-axis PSF with no apodizer after aperture stop (red curve), and on-axis PSF with apodizer placed after the aperture stop (blue curve).

Figure 6 shows a comparison of the contrast performance (left column) and the corresponding mask reflection (right column) with respect to the distance from the star PSF of EvWaCo for the V- and R- bands of the Johnson-Cousins photometric system to illustrate the quasi-achromatic behavior of the setup. The distance is expressed in λ_C/D_{maj} where λ_C is the central wavelength of the corresponding photometric band.

In the R- and V-band, we notice that the IWA is close to $4 \lambda_C/D_{\text{maj}}$ (respectively, close to $5 \lambda_C/D_{\text{maj}}$ in the V-band) instead of $3 \lambda_C/D_{\text{maj}}$ in the I-band. This spectral variation of the IWA value is attributed to the contact area between the prism and the lens that constitute the coronagraphic mask as fully discussed in a previous paper [5]. We also notice that in both the R- and V-Band, the contrast varies between a few 10^{-6} to a few 10^{-7} at distances comprised between the IWA and 10 Airy radii from the PSF center. These contrast levels are similar to the contrasts simulated on the I-band over the same distance range. The only difference is the value of the IWA slightly varies with the wavelength. We, thus, conclude that, at least in theory, the contrast performance of EvWaCo are constant over the wide spectral band covered by the three spectral bands from $\lambda_C = 473$ nm to $\lambda_C = 900$ nm.

4.2 Advantages of EvWaCo for space-based observations

EvWaCo is a simple, compact and cost-effective coronagraph with theoretical contrasts of a few 10^{-6} with an IWA slightly varying between $3 \lambda_C/D$ and $5 \lambda_C/D$ in the V-, R-, and I-bands. One of the main advantages of EvWaCo is to provide the capability to collect the light transmitted by the focal plane mask and, thus, to measure the WFE in the vicinity of the coronagraphic mask. We believe that this capability to measure the wavefront in the immediate proximity of the coronagraphic mask is a significant advantage to control the low order distortions of the beam incident on this mask. In the framework of a space mission, this possibility can be used to i) precisely control the telescope pointing direction to stabilize the central PSF on the coronagraphic mask, and ii) to correct the wavefront distortions due to the manufacturing errors as well as the misalignments induced by the launching, the zero-gravity and thermo-elastic effects. Another advantage is the quasi-gaussian transmission of the coronagraphic mask that makes possible the use of simple apodization profiles (gaussian in the present case) to significantly improve the contrast performance at a minimum cost as shown in the previous section.

We consider that all these advantages make EvWaCo a serious candidate for the future space-based mission that will require a cost-effective system to provide deep contrasts at distances typically comprised between 3 and 10 Airy radii from the star center. This is beneficial especially in the perspective of the application of EvWaCo to High Dispersive Coronagraph that will require some coronagraph providing deep contrasts stable over very wide spectral bands [6].

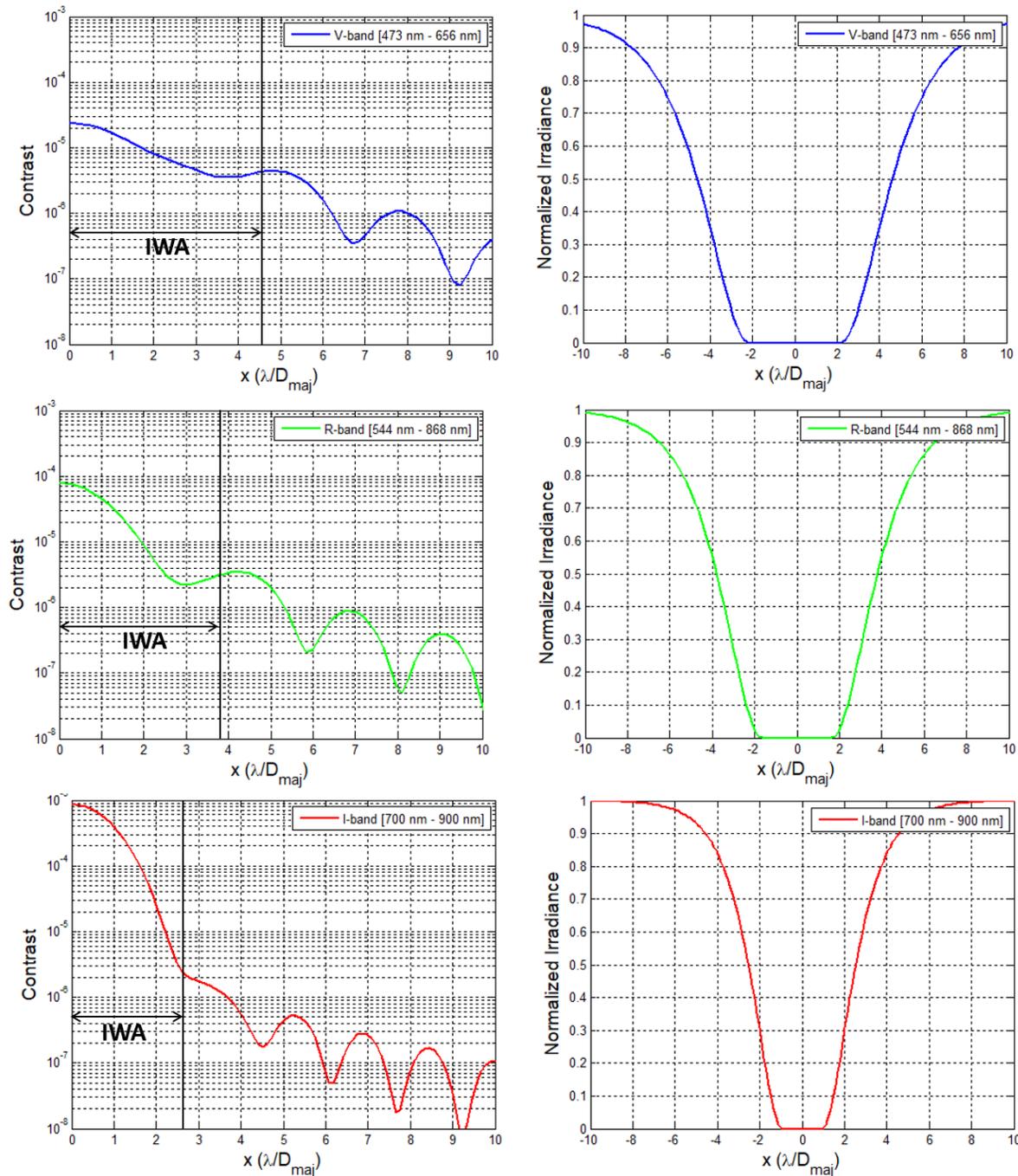


Figure 6. Comparison of contrast performance among the different bandpass filters of the Johnson-Cousins photometric system: V-band (blue curve), R-band (green curve), and I-band (red curve) in terms of λ_c/D_{maj} where D_{maj} is the major axis of the elliptical entrance pupil and λ_c is the central wavelength of the photometric I-band which are the following: $\lambda_c = 525$ nm for the V-band with a spectral domain of [473 nm, 656 nm], $\lambda_c = 600$ nm for the R-band with a spectral domain of [544 nm, 868 nm], and $\lambda_c = 800$ nm for the I-band with a spectral domain of [700 nm, 900 nm].

CONCLUSIONS

In this paper, we presented the current capabilities of the EvWaCo coronagraph and its potential advantages in view of space-based observations. Using the current testbed at NARIT, we showed the detection of a faint companion located at $15 \lambda_c/D$ and $30 \lambda_c/D$ over the full photometric I-band in unpolarized light with a very good SNR. We also presented the full prototype design that includes an adaptive optics control loop that will be tested on the 2.4 m Thai National Telescope in horizon 2020 with the corresponding optical performance specifications. Finally, we showed by using the EvWaCo numerical model of the companion channel that we should be able to reach a contrast of a few 10^{-6} at the respective IWA comprised between $3 \lambda_c/D$, $4 \lambda_c/D$ and $5 \lambda_c/D$ of the V-, R- and I-bands in unpolarized light.

REFERENCES

- [1] Rabbia Y., “Shared constraints and specific characters in Very High Dynamics Imaging”, in Proceedings of Astronomy with High Contrast Imaging, C.Aime and R. Soummer, eds., EAS Publication Series 8, pp. 65-78, 2003.
- [2] Zhu S., Yu A.D., Hawley D., Roy R., “Frustrated Total Internal Reflection: A demonstration and review,” American Journal of Physics 54 (7), 601-606 (1986).
- [3] Buisset, C., Rabbia, Y., Lepine, T., Alagao, M.A., Ducrot, E., Poshyachinda, S. and Soonthornthum, B., “Study of a coronagraphic mask using evanescent waves,” Optics Express 25 (7), 7273-7287 (2017).
- [4] Alagao M.A., Buisset C., Rabbia Y., Lepine T., Poshyachinda S., Soonthornthum B., “Development status and performance of the evanescent wave coronagraph testbed”, Proc. SPIE 10400, Techniques and Instrumentation for Detection of Exoplanets VIII (2017).
- [5] C. Buisset, T. Lepine, E. Thiebaut, M. Langlois, M. Tallon, M.A. Alagao, I. Tallon-Bosc, Y. Rabbia, S. Poshyachinda, B. Soonthornthum, E. Ducrot, “The Evanescent Wave Coronagraph Project: setup results and demonstrator preliminary design, Proc. SPIE 10706, Astronomical Telescopes and Instrumentation (2018).
- [6] Wang, J., Mawet, D., Ruane, G., Hu, R., Benneke, B., “Observing exoplanets with high dispersion coronagraphy. I. The Scientific Potential of Current and Next-Generation Large Ground and Space Telescopes”, The Astronomical Journal, 153:183, April 2017.