Challenging Theory with Roman:
From Planet Formation to Cosmology
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The Coherent Differential Imaging on Speckle Area Nulling Method for Suppression of Fluctuating Speckles

Kenta Yoneta[1]

Jun Nishikawa[1,2,3], Yutaka Hayano[1,2], Masatsugu Iribe[4], Kodai Yamamoto[5], Ryo Tsukui[6], Naoshi Murakami[7], Mizuki Asano[7], Yosuke Tanaka[8,3], Motohide Tamura[9,3,1], Takahiro Sumi[10], Toru Yamada[11], Olivier Guyon[1,12,3], Julien Lozi[1], Vincent Deo[1], Sébastien Vievard[1,3], Kyohoon Ahn[13,1]

1: National Astronomical Observatory of Japan, 2: The Graduate University for Advanced Studies, 3: Astrobiology Center, 4: Osaka Electro-Communication University, 5: Kyoto University, 6: LogistLab Inc., 7: Hokkaido University, 8: Tokyo University of Agriculture and Technology, 9: The University of Tokyo, 10: Osaka University, 11: Japan Aerospace Exploration Agency, 12: The University of Arizona, 13: Korea Astronomy and Space Science Institute

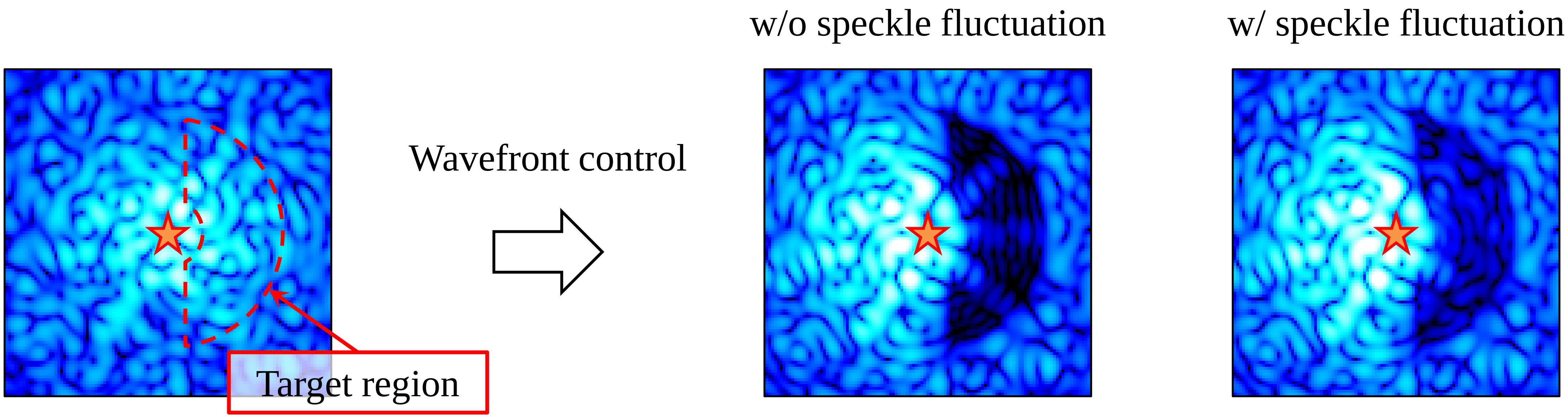
Introduction

◆**Direct detection of Earth-like exoplanets requires contrast of 10^{-10} level**

- Scattered stellar light (speckles) can be suppressed by wavefront sensing and control system
- However, fluctuating speckles caused by deformation of instruments will remain

◆**Coherent Differential Imaging on Speckle Area Nulling (CDI-SAN)[1]**

- Post-processing technique to suppress the fluctuating speckles
- Only control software for wavefront control device and camera is required
- **This method could be effective for Roman/CGI to achieve contrast of 10^{-10} level**

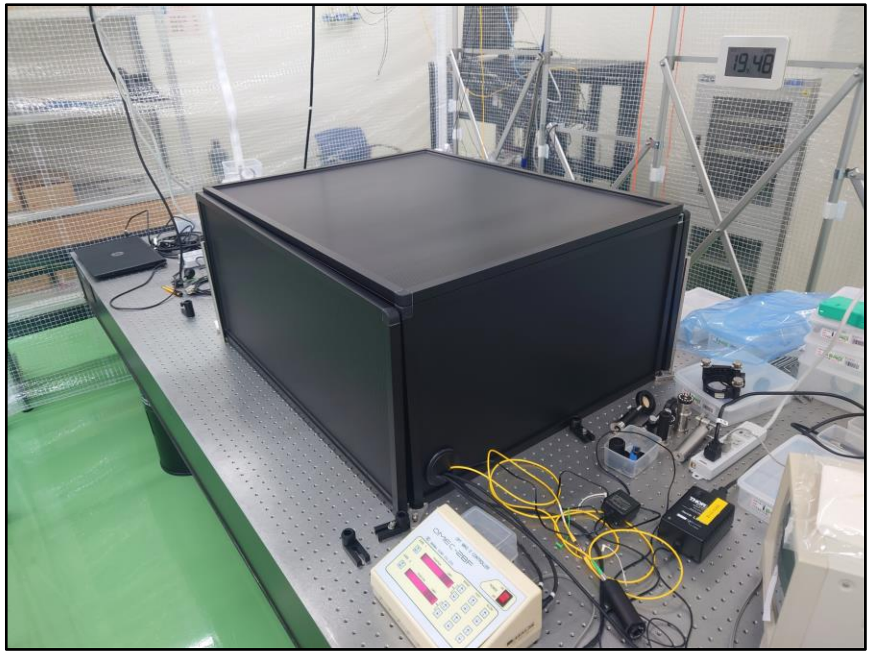


[1] J. Nishikawa, *Astrophys. J.*, **930**, 163 (2022).

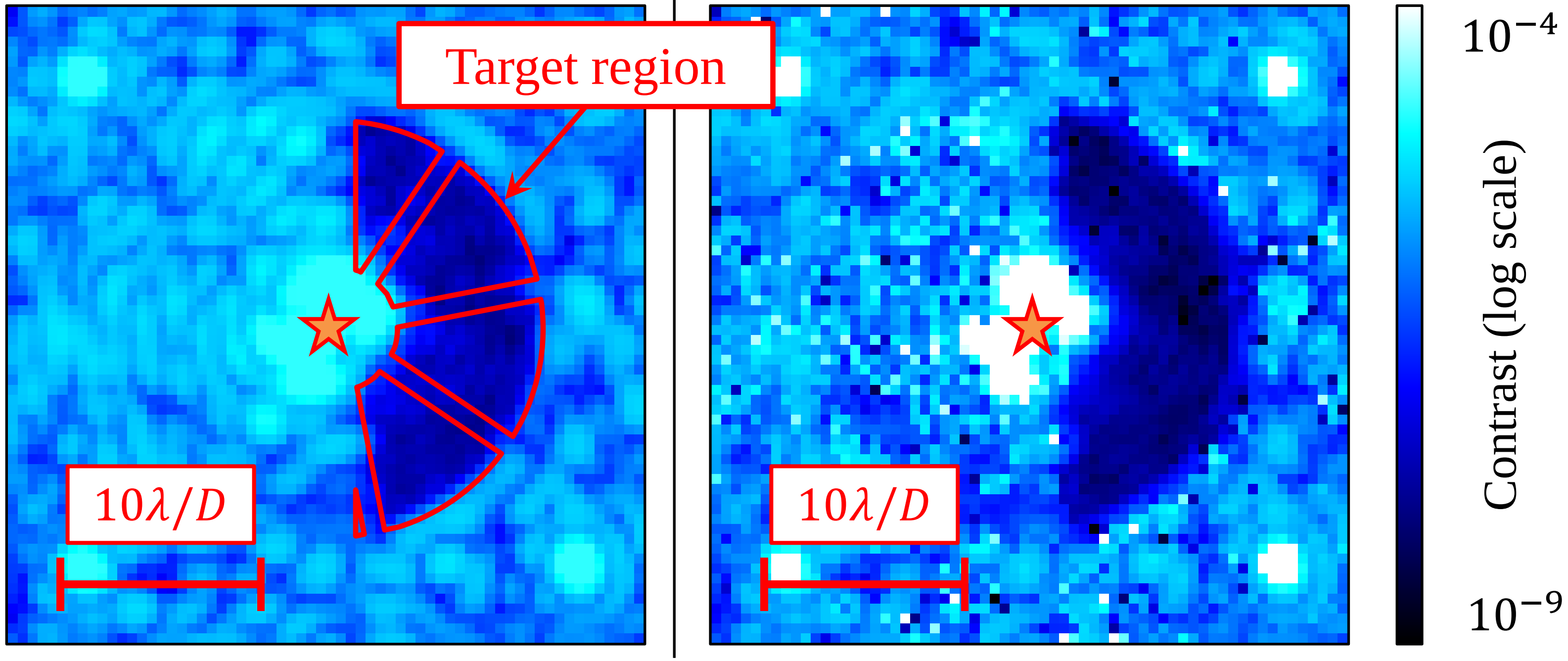
Laboratory Demonstration for Suppression of Fluctuating Speckles

◆**The contrast was improved in speckle fluctuating situation**

Facility at NAOJ[1]



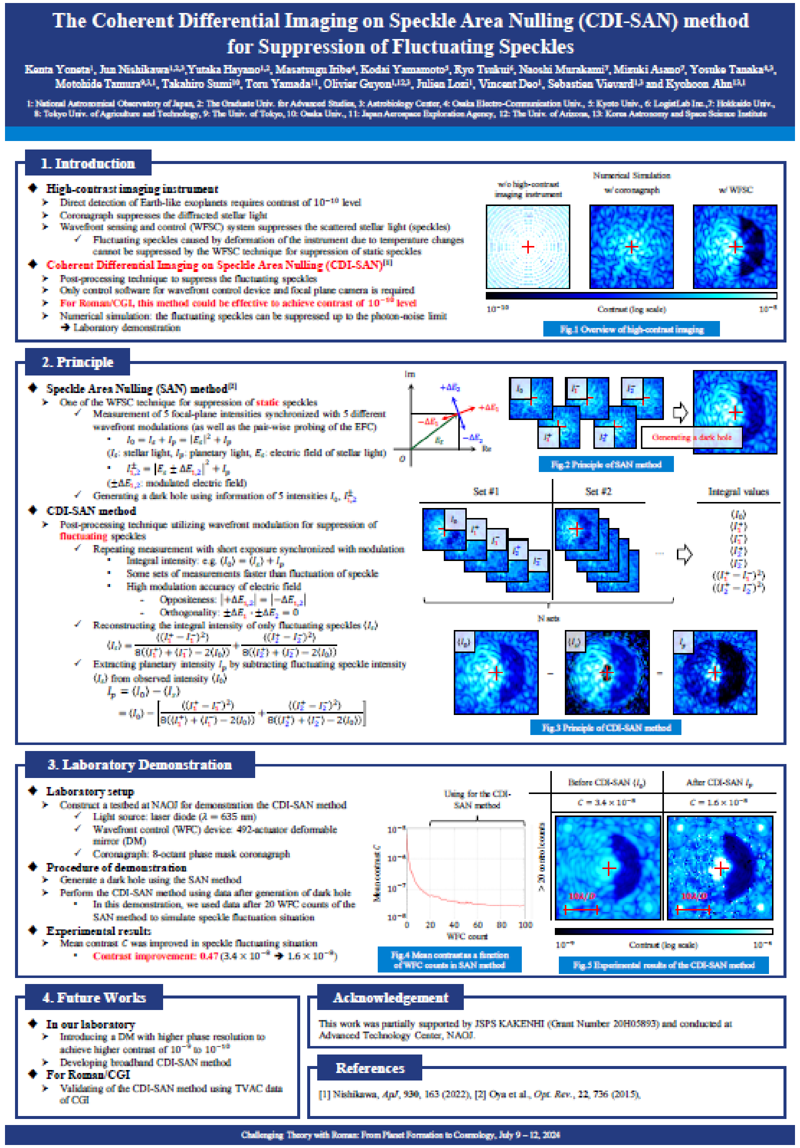
Before CDI-SAN	After CDI-SAN
Mean contrast $= 3.4 \times 10^{-8}$	Mean contrast $= 1.6 \times 10^{-8}$



Contrast improvement was 0.47

[1] K. Yoneta et al., *Proc. SPIE*, **12680**, 126800D (2023).

National Astronomical Observatory of Japan



The Coherent Differential Imaging on Speckle Area Nulling (CDI-SAN) method for Suppression of Fluctuating Speckles

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1. Introduction

- **High-contrast imaging instrument**
  - Direct detection of Earth-like exoplanets requires contrast of 10^{-10} level
  - Coronagraph suppresses the diffracted stellar light
  - Wavefront sensing and control (WFSC) system suppresses the scattered stellar light (speckles)
    - Fluctuating speckles caused by deformation of the instrument due to temperature changes cannot be suppressed by the WFSC technique for suppression of static speckles
- **Coherent Differential Imaging on Speckle Area Nulling (CDI-SAN)[1]**
  - Post-processing technique to suppress the fluctuating speckles
  - Only control software for wavefront control device and focal plane camera is required
  - For Roman/CGI, this method could be effective to achieve contrast of 10^{-10} level
  - Numerical simulation: the fluctuating speckles can be suppressed up to the photon-noise limit
    → Laboratory demonstration

Fig.1 Overview of high-contrast imaging

2. Principle

- **Speckle Area Nulling (SAN) method[2]**
  - One of the WFSC technique for suppression of static speckles
    - Measurement of 5 focal-plane intensities synchronized with 5 different wavefront modulations (as well as the pair-wise probing of the EFC)
      - $I_0 = I_s + I_p = |E_s|^2 + I_p$
      (I_s: stellar light, I_p: planetary light, E_s: electric field of stellar light)
      - $I_{1,2}^{\pm} = |E_s \pm \Delta E_{1,2}|^2 + I_p$
      ($\pm\Delta E_{1,2}$: modulated electric field)
    - Generating a dark hole using information of 5 intensities I_0, $I_{1,2}^{\pm}$
- **CDI-SAN method**
  - Post-processing technique utilizing wavefront modulation for suppression of fluctuating speckles
    - Repeating measurement with short exposure synchronized with modulation
      - Integral intensity: e.g. $\langle I_0 \rangle = \langle I_s \rangle + I_p$
      - Some sets of measurements faster than fluctuation of speckle
      - High modulation accuracy of electric field
        - Oppositeness: $|+\Delta E_{1,2}| = |-\Delta E_{1,2}|$
        - Orthogonality: $\pm\Delta E_1 \cdot \pm\Delta E_2 = 0$
    - Reconstructing the integral intensity of only fluctuating speckles $\langle I_s \rangle$
    $$\langle I_s \rangle = \frac{\langle (I_1^+ - I_1^-)^2 \rangle}{8(\langle I_1^+ \rangle + \langle I_1^- \rangle - 2\langle I_0 \rangle)} + \frac{\langle (I_2^+ - I_2^-)^2 \rangle}{8(\langle I_2^+ \rangle + \langle I_2^- \rangle - 2\langle I_0 \rangle)}$$
    - Extracting planetary intensity I_p by subtracting fluctuating speckle intensity $\langle I_s \rangle$ from observed intensity $\langle I_0 \rangle$
    $$I_p = \langle I_0 \rangle - \langle I_s \rangle = \langle I_0 \rangle - \left[\frac{\langle (I_1^+ - I_1^-)^2 \rangle}{8(\langle I_1^+ \rangle + \langle I_1^- \rangle - 2\langle I_0 \rangle)} + \frac{\langle (I_2^+ - I_2^-)^2 \rangle}{8(\langle I_2^+ \rangle + \langle I_2^- \rangle - 2\langle I_0 \rangle)}\right]$$

Fig.2 Principle of SAN method

Fig.3 Principle of CDI-SAN method

3. Laboratory Demonstration

- **Laboratory setup**
  - Construct a testbed at NAOJ for demonstration the CDI-SAN method
    - Light source: laser diode ($\lambda = 635$ nm)
    - Wavefront control (WFC) device: 492-actuator deformable mirror (DM)
    - Coronagraph: 8-octant phase mask coronagraph
- **Procedure of demonstration**
  - Generate a dark hole using the SAN method
  - Perform the CDI-SAN method using data after generation of dark hole
    - In this demonstration, we used data after 20 WFC counts of the SAN method to simulate speckle fluctuation situation
- **Experimental results**
  - Mean contrast C was improved in speckle fluctuating situation
    - Contrast improvement: 0.47 (3.4×10^{-8} → 1.6×10^{-8})

Fig.4 Mean contrast as a function of WFC counts in SAN method

Fig.5 Experimental results of the CDI-SAN method

4. Future Works

- **In our laboratory**
  - Introducing a DM with higher phase resolution to achieve higher contrast of 10^{-9} to 10^{-10}
  - Developing broadband CDI-SAN method
- **For Roman/CGI**
  - Validating of the CDI-SAN method using TVAC data of CGI

Acknowledgement

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References

[1] Nishikawa, *ApJ*, 930, 163 (2022), [2] Oya et al., *Opt. Rev.*, 22, 736 (2015).

Thank you for your attention!

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