Precision Photometric Calibration with Alternating Incoherent Satellite Speckles

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ABSTRACT

Exoplanet characterization relies on extracting precision astrometry (orbits) and photometry (spectra, time variation) measurements from high contrast images. Obtaining such measurements is challenging due to residual starlight speckles and the fact that the central stellar PSF core is blocked by the coronagraph. In post coronagraphic images it becomes quite difficult to measure the relative position and intensity of companion with respect to the stellar as it is blocked by the coronagraph. This issue has been addressed by imposing a periodic phase grid on the Deformable Mirror of SCExAO system to generate satellite speckles which are incoherent with underlying speckle halo for calibration. We report on-sky measurements of the photometric stability of such incoherent speckles over a 15 minute period time. We demonstrate that for relatively fainter speckles, unknown background noise (speckles) creates a bias in the photometric measurement. We show that, by subtracting two frames with two different speckle patterns, we address this issue and obtain unbiased measurements. This technique will be beneficial for future large telescopes where they have the potential to obtain diffraction limited images.

Keywords: Photometry, Satellite Speckles, High Contrast Imaging, Coronagraphy, Instrumentation, Adaptive Optics

1. INTRODUCTION

Direct imaging of nearby faint companion, circumstellar disk gives an insight to the planet formation theory, characterization and allows astronomers to look for life beyond our solar system. Several high contrast imaging instruments such as Gemini Planet Imager (GPI)[1], Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE)[2], Magellan Adaptive Optics (MagAO)[3] and Subaru Coronagraphic Extreme Adaptive Optics (SCExAO)[4] are evolving to produce high resolution direct images of these objects at small angular separation from their stellar host. Relative accurate photometry plays a key role in determining the physical properties of the companion such as temperature, mass, spectra (chemical composition). In non-coronagraphic images, relative photometry(or astrometry) is easily obtained by simultaneously comparing the flux(or position) of the targeted object with their stellar host's Point Spread Function(PSF) in the same exposure. Whereas, in coranagraphic images, the central starlight is blocked by an occulter or mask and it becomes quite challenging to perform relative photometry or astrometry in these images. This issue has been addressed by placing a regular diffractive grid in the pupil plane to create a set of off-axis symmetric copies (or satellite spots) of the central PSF which are then used as calibrators for the nearby objects[5]. The off-axis copies thus formed may interfere

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with the background speckles to form spots which are not exact replicas of the central PSF. The phase of these calibrators are switched between 0 and π at high speed (typically ~kHz)[6], time averaged within an exposure to get temporarily incoherent copies of the central PSF. However, there still remains incoherent flux beneath the satellite speckle which can ultimately limit our calibration. In subsequent sections in this article, we propose and demonstrate that by subtracting two closet frames with two different speckle patterns, we can achieve a much more precise photometric calibration with these satellite speckles.

2. SATELLITE SPOT FORMATION

The physics behind the formation of satellite spot is based on Huygens-Fresnel propagation principle after diffraction grating. Adding a periodic grid phase mask or amplitude mask in the pupil plane creates a pair or more off-axis symmetric copies of the central PSF. Each spot thus formed has its own phase and amplitude. These spots can be placed at a known location with a pre-defined contrast w.r.t PSF core by adjusting the grid parameters such as spatial grid frequency, amplitude of aberration etc. In the left of figure 1, a sinusoidal 1-D wave has been applied to the pupil plane phase function (similar to Subaru Telescope's pupil) and the right shows the corresponding focal plane image thus generated. Two or more satellite spots can be seen the right of figure 1. As the light from the central PSF is diffracted away to generate the satellite spots, these spots thus have low resolution spectra of the central star and can be used to track the obscured PSF core.

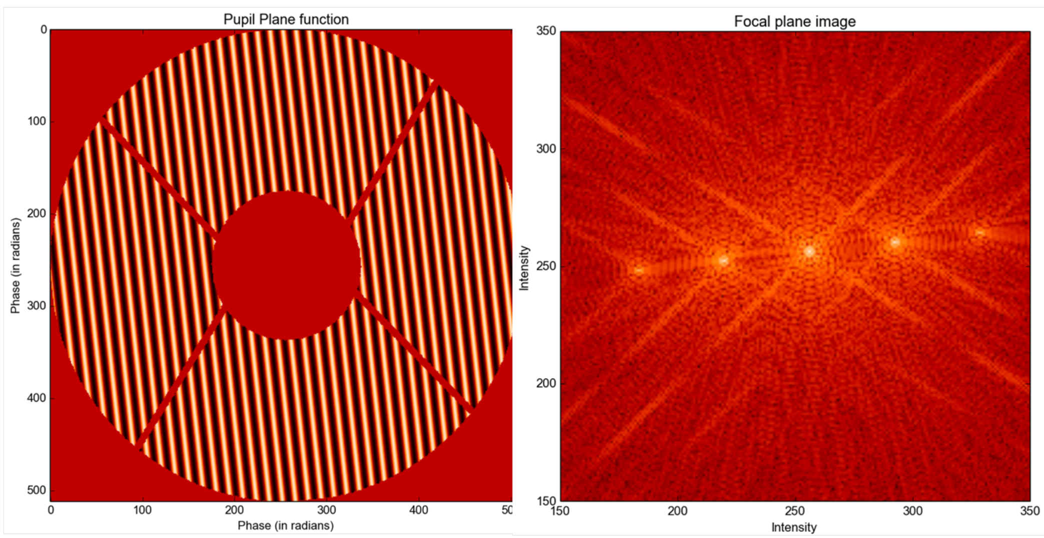

Figure 1. Sinusoidal phase modulation in the pupil plane creates monochromatic satellite spots in the focal plane

In post-coronagraphic images, the relative flux between the central PSF and the companion is registered through the satellite spot. At first, the relative flux between the satellite spot and the companion is measured and then this ratio is scaled with the pre-determined contrast of satellite spot and PSF core to compute the relative flux of the companion and the central star. Accurate measurement of the relative flux between satellite spot and the companion is the key to precise photometry. For ground based telescopes, several factors such as the object air mass, the telescope vibration, seeing, sky transmission lead to Strehl variation, thus introduce aberration in the flux measurement. The effect of Strehl variation on the satellite spot and the companion is uniform (neglecting chromatic and off-axis aberration). Therefore, relative flux measurement eliminates the strehl variation (neglecting the quasi-static background level). Other factors such as aberration in the instrument optics, non-common path adaptive optics error, detector readout noise etc can introduce quasi-static background speckles noise. These background speckle interferes with the satellite spots and thus form spots which are not true replicas of the host star. The intensity of the resultant spot thus formed comprises of the actual intensity of the satellite spot, background speckle(incoherent) and the coherent intensity due to their interference. The phase of the satellite spot is switched between 0 and π within an exposure, time averaged to remove the coherent flux. However, the remaining incoherent flux (i,e A_h^2 in Equation 4 of Jovanovic et al. (2015)[6]) due to the background can create a bias in our flux measurement. A new approach to remove this incoherent background is to measure and subtract them dynamically from the true satellite spot. Subtracting two frames with different speckle patterns gives us an estimate of the amount of incoherent flux lying beneath the satellite spot without losing calibrators for each frame. Subtracting a frame from its closet(or most likely neighboring frame) frame can remove the underlying speckle halo, and then measuring the relative flux can eliminate the effect of Strehl, thus can lead to more accurate photometry.

3. ON-SKY IMPLEMENTATION

In this section, we briefly discuss the implementation of our technique of alternating the speckle pattern in SCExAO-CHARIS system. SCExAO is an extreme Adaptive Optics instrument dedicated towards imaging exoplanets, circumstellar disk and validating technology for future large telescopes. The Coronagraphic High Angular Resolution Imaging Spectrograph (CHARIS)[7] is an integral field spectrograph which takes extreme AO corrected light from SCExAO. Figure 2 gives the schematic representation of the SCExAO bench along with its real picture with all other modules at the Nasmyth platform of Subaru Telescope.

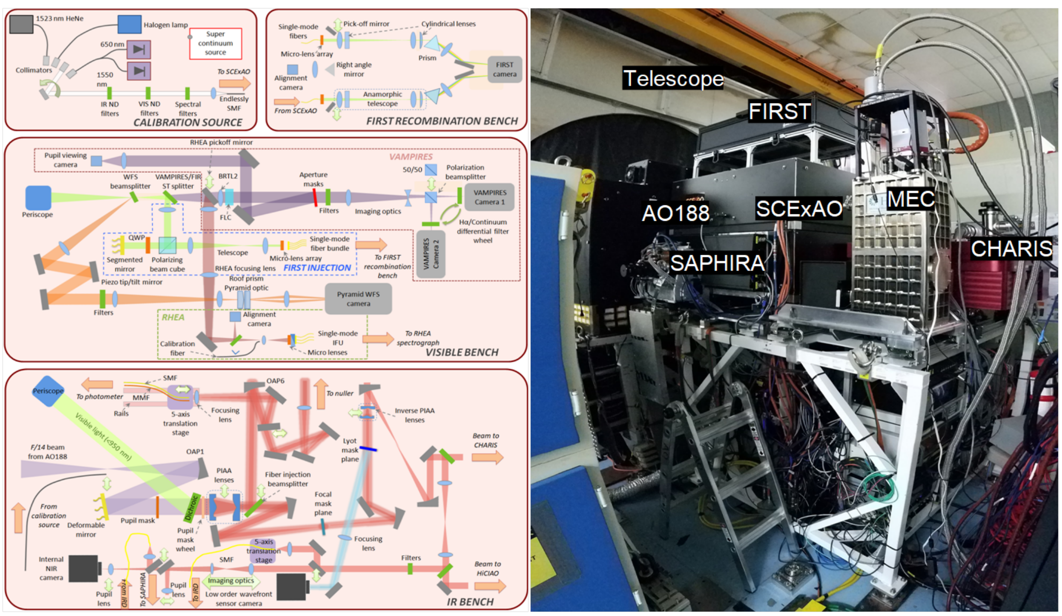

Figure 2. Left: A detailed optical layout the SCExAO bench, Right: The actual picture of the instrument mounted at the Nasmyth IR platform. AO188 gives partially coarse AO corrected light to SCExAO for further fine AO correction (can be seen in the middle,three tier instrument large black box), CHARIS (the red box) with other modules

We applied a sinsusoidal waffle pattern on the MEMs based Deformable Mirror(DM)in SCExAO system to generate artificial satellite spots. The phase of this sinsusoidal pattern was switched between 0 and π at 2kHz to generate incoherent satellite speckle. Between each CHARIS exposures, the grid pattern were switched. Figure 3 shows there consecutive CHARIS frames taken with target HR8799 with different speckle pattern.

On-sky data were taken on the target β-Leo (A3 star type, Hmag =1.92) using low resolution broadband mode(R=18.2) of CHARIS. The raw data were reduced using the CHARIS data reduction pipeline[8]. We applied sinsuoidal wave of amplitude 8.8 nm to create satellite spots which were $\sim 10^3$ times fainter than the central PSF. Regular satellite spots (formed with 50 nm, or 25nm DM amplitude) prevents simultaneous measurement in the visible and infrared regime as these spots tends to get much more brighter in visible instrument(VAMPIRES)and saturate the visible science detector. Also, with the fainter satellite speckle we can achieve higher contrast of the grid spot w.r.t PSF core which can act as an ideal calibrator for faint objects such as exoplanets. Figure 4 left, shows two consecutive CHARIS exposure for the target β-Leo having two alternated speckle patterns where

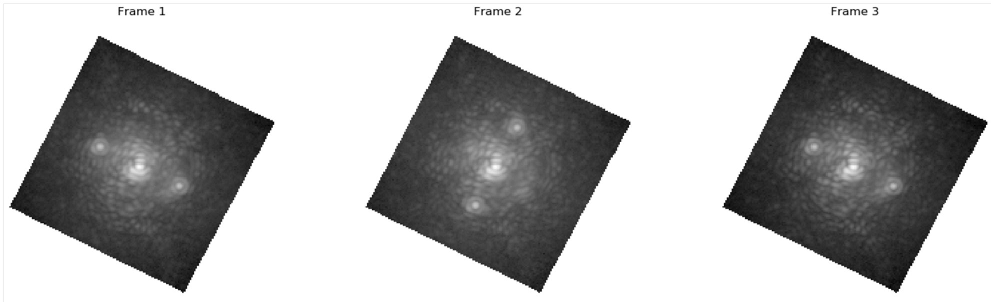

Figure 3. Images of three consecutive reduced data slices of HR8799 obtained from CHARIS at 1630 nm showing two alternate speckle pattern for illustration of our technique.

the grid spots are barely visible. The spots are placed at a separation of $11.25\lambda/D$ from the PSF center. While figure 4 right, shows the subtracted images of these frames where this speckle pattern are clearly visible. The flux and position of this subtracted speckle spots were measured using aperture photometry.

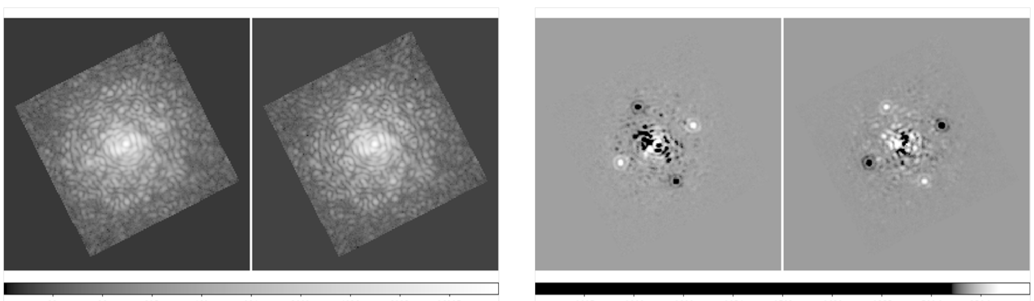

Figure 4. Left: Images of two consecutive reduced data slices of β Leo obtained from CHARIS at 1744 nm with two alternate fainter speckle patterns where they are barely visible. Right: Images of the same two data slices after subtraction frame. After subtracting two consecutive frames, the calibration speckles can be clearly seen.

The fluxes of these speckle grid flux (after subtraction) were measured to a precision of approximately 5% in H-band for 10 sec frame exposure over a period of 10 minutes. We also obtained a photometry precision of $\sim$7% in the ratio of fluxes of a pair of satellite speckle in an exposure. Assuming random background level, the error in the measurement of companion to host flux ratio directly scales to the error associated with the companion and satellite spot flux measurement. Therefore, we infer that the companion and host star contrast can be measured to an accuracy of 7%. Further, this precision increases with more number of data frames, indicating that our measurement has no significant biased background level.

4. CONCLUSION

In this article we discussed the importance of satellite spots in post-coronagraphic images and the need to change their patterns for each exposures. We deployed artificial incoherent satellite spots with alternating pattern on a high resolution integral field spectrometer to do precision photometry. This technique aims at improving the stability of satellite spots where the background level is dominated by quasi-static speckles. We demonstrated a practical solution to photometric calibration challenging in high contrast imaging. This technique is applicable for orbits, spectra and time variation measurements from high contrast images.

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References

1. B Macintosh et al. First light of the gemini planet imager. *Proceedings of the National Academy of Sciences*,111(35):12661-12666, 2014. ISSN 0027-8424. doi: 10.1073/pnas.1304215111.

2. J.L. Beuzit et al. Sphere: a 'planet finder' instrument for the vlt. *Ground-based and Airborne Instrumentation for Astronomy II*, volume 7014, page 701418, 2008. doi: 10.1117/12.790120.

3. Jared R. Males et al. Magao-x: project status and first laboratory results, 2006. URL https://doi.org/10.1117/12.2312992.

4. N. Jovanovic et al. The subaru coronagraphic extreme adaptive optics system: Enabling high-contrast imaging on solar system scales. *Publications of the Astronomical Society of the Pacific*, 127(955):890, 2015b. URL http://stacks.iop.org 1538-3873/127/i=955/a=890.

5. Anand Sivaramakrishnan and Ben R. Oppenheimer. Astrometry and photometry with coronagraphs. *The Astrophysical Journal*, 647(1):620, 2006. URL http:// stacks.iop.org/ 0004-637X/647/i=1/a=620.

6. N. Jovanovic, O. Guyon, F. Martinache, P. Pathak, J. Hagelberg, and T. Kudo. Artificial incoherent speckles enable precision astrometry and photometry in high-contrast imaging. *The Astrophysical Journal Letters*, 813(2):L24, 2015a. URL http://stacks.iop.org/2041-8205/813/i=2/a=L24.

7. T. Groff et al. First light of the charis high-contrast integral field spectrograph. *Society of Photo Optical Instrumentation Engineers (SPIE) Conference Series, volume 10400 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 1040016, sep 2017. doi: 10.1117/12.2273525.

8. Timothy D. Brandt et al. Data reduction pipeline for the charis integral field spectrograph i: detector readout calibration and data cube extraction. *Journal of Astronomical Telescopes, Instruments, and Systems*, 3:048002, 2017. doi: 10.1117/1.JATIS.3.4.048002.