Improving the broadband contrast at small inner working angles using image sharpening techniques

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Abstract. The detection of extrasolar planets, using both space- and ground-based telescopes, is one of the most exciting fields in astronomy today. From the ground, the upcoming Extremely Large Telescopes will offer a significant increase in our capability to directly image exoplanets and could potentially lead to the direct detection of planets in the habitable zone. To obtain contrasts better than $10^{-7}$-$10^{-9}$ requires precise wavefront control algorithms. Although wavefront control techniques, such as Electric Field Conjugation, stroke minimization and speckle nulling, have been already developed and will soon be operational on 8-m class telescopes, they primarily function in monochromatic light and at moderate separations ($r > 3 \lambda/D$). While wavefront control simulations combining polychromatic light and smaller inner working angles (1.2 $\lambda/D$ for example) have shown promising results, experimental verification is still ongoing. In this paper, we discuss the challenges emerging when pushing the limits of high-contrast imaging and present our latest contrast results using wavefront control techniques optimized for small separations. This work is performed using the NASA Ames Coronagraph Experiment (ACE) laboratory testbed located in California.

1 Introduction

Direct imaging of exoplanets is a powerful characterization technique as it allows observations of the planet itself as opposed to indirect techniques where the companions properties can only be inferred. Furthermore, direct imaging can cover multiple wavelengths or provide polarimetric data which offers information about the companion’s relationship with the parent star as well as its composition.

With the improvement of imaging techniques, the development of nanometer precision sensing as well as correction devices, direct imaging is now advancing the study of exoplanets. The detection and direct imaging of planets and particularly earth-like planets is a very exciting and dynamic field both from the ground and space. From the ground, instruments such as the Gemini Planet Imager (GPI) [1] and SPHERE [2] are scheduled to come online during the year 2014. They aim to reach contrasts of $10^{-7}$ enabling Jupiter-like planet detections along with spectroscopic and polarimetric characterization. The current level of technology for space-based applications is not sufficiently mature to directly detect earth-like planets yet. One of the potential missions that will serve as a precursor for more powerful earth-like planet imaging mission is called EXCEDE, EXoplanetary Circumstellar Environments and Disk Explorer [3], [4]. EXCEDE is currently undergoing technology development implemented by a partnership between NASA Ames Research Center, Lockheed Martin, and the University of Arizona, and

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EXCEDE will use a 0.7m primary mirror, unobstructed optical telescope in combination with a Phase Induced Aperture Apodization (PIAA) coronagraph. It features two 20% bands, one at 0.4 and one at 0.8 \( \mu m \) with polarimetry. Wavefront control is enabled by a Low Order Wavefront Sensor (LOWFS) and a MicroElectro Mechanical System deformable mirror (MEMS DM). More information on the mission can be found in Belikov et al. [5]. In short, the main astronomical science goals of this mission are listed below:
- Characterize the circumstellar environments in habitable zones and assess the potential for habitable planets;
- Study the presence of a disk, signpost for existence of planetary systems;
- Spatially resolved imaging reveals its structure and traces the presence of massive planets;
- Quantify the amount of exo-zodical light to estimate its interference with future planet detection missions;
- Understand the formation, evolution, and architecture of planetary systems;
- Develop and demonstrate advanced coronagraphy in space, enabling future exoplanet missions;

Derived from these science goals, the requirements for the final performance of the instrument is to reach a raw contrast of \( < 10^{-6} \) between 1.2 and 2.0 \( \lambda/D \) simultaneously with a raw contrast of \( > 10^{-7} \) between 2 and 22 \( \lambda/D \). We are currently working on obtaining these levels of contrasts both in air at the Ames Coronagraph Experiment (ACE) laboratory testbed and in vacuum at Lockheed Martin vacuum chamber. In this paper, we will focus on the ACE testbed. We first present the ACE laboratory in section 2 combined with the required calibration and wavefront control algorithms needed to reach the required contrast. We show in section 3 that reaching such contrast necessitates high stability control. The laboratory results are presented in section 4 and finally conclusions and future work are presented in section 5.

2 The ACE Laboratory

The Ames Coronagraph Experiment (ACE) laboratory (see Figure 1) is located at NASA Ames.

The purpose of the ACE testbed is to obtain high-contrast images mostly at small inner working angles. Our current laboratory milestone, inline with the EXCEDE requirements, is to reach a contrast better than \( 10^{-6} \) in a crescent region from 1.2 to 2 \( \lambda/D \) and better than \( 10^{-7} \) in a crescent region from 2 to 4 \( \lambda/D \) in monochromatic light over a single sided dark zone (see Figure 2).

Other groups have used similar testbed for high-contrast imaging and obtained contrasts larger than \( 10^{-8} \) at slightly less aggressive separations than the ones targeted in this experiment [6], [7], [8], [9].

The primary components of the optical design are: PIAA (Phase Induced Apodized Amplitude) coronagraph [10] (see Figure 3-right), a 32 by 32 MEMS DM from Boston Micromachine Corporation (see Figure 3-left) to control the wavefront and a Low Order Wavefront Sensor (LOWFS) [11]. The optics are housed in a temperature controlled environment that uses water cooling.
The optical layout is rather typical for a high-contrast imaging testbed [8], [9]. The light is injected in the system using a fiber connected to an XYZ stage. The stage is motorized and
operated in closed-loop with the LOWFS. The light then goes directly to a set of PIAA mirrors, made by Tinsley (see figure 3-right). The PIAA mirrors’ clear aperture is 90 mm and their equivalent focal length 900 mm. The magnification of an on axis-beam is equal to 3.5, meaning that the rays at the output of the PIAA system are mostly concentrated on a diameter 3.5 times smaller than at the input. We then use an aperture, slightly smaller than the beam size to remove wavefront errors introduced by the edges of the PIAA mirrors. The MEMS DM is placed after a re-imaging lens in a converging beam before the focal plane occulter (FPO). The FPO is either a C shape mask or a round mask deposited on a piece of glass. In both cases, the center of the mask is reflective and sends the central light (the low order modes) to the LOWFS. The LOWFS filters fast tip/tilt motions by sending corrections to the input fiber with a cutoff frequency of 10 Hz. It also measures and corrects for pointing shifts introduced in the system originating from instabilities or wavefront control algorithms. More details on the LOWFS can be found in Lozi et al [12]. The Lyot stop is placed in the converging beam produced by a last re-imaging lens. It is conjugated neither to the MEMS DM nor the first PIAA mirror mainly due to opto-mechanical constraints as the iris used as the Lyot mask could not close to the proper size if placed in the plane conjugated to the MEMS DM. However, this is not that crucial because the current setup does not have an inverse PIAA. Therefore, the position of the pupil is not as defined and precise as if calculated using standard geometrical optics. The other consequence of not having an inverse PIAA is that the final point spread function (PSF), called $PSF_{sky}$ is more magnified than the PSF found without the PIAA called $PSF_{system}$. The magnification of the PSF is 3.5 (equal to the magnification of the PIAA system).

The testbed hardware is primarily controlled using Labview. This includes the position control of the optical fiber, the mask position, the deformable mirror and the camera. An important consideration is that the ACE testbed enables any image-based wavefront algorithms to be used to obtain a dark zone in chosen regions. It is flexible and easily modifiable.

### 2.2 Calibration

Such tight requirements especially close to the PSF core of the parent star implies a very precise calibration of the system. Before each run, we precisely align the input fiber to the PIAA system (see Fig. 1). This avoids extra strong aberrations such as the typical pineapple shape aberration seen with misaligned PIAA systems. We then measure the intensity peak of the PSF, the camera pixel scale in $\lambda/D$, the orientation of the MEMS relative to the bench. Several times per run we also perform an inner working angle (IWA) calibration. This is done by moving the PSF at the desired IWA and then moving mask over the PSF until it covers 50% of the light. It is repeated regularly during a wavefront control run as the algorithm causes the PSF center of gravity to shift slightly. The whole calibration is done using an automated and repeatable Labview code.

### 2.3 Wavefront control algorithms

Because of aberrations and residual diffraction, using an optical coronagraph is only the first but important step toward achieving the contrast goal presented in section 2. Along with it, one needs to use wavefront control techniques or nulling techniques to create darker regions. Nulling techniques have been demonstrated in multiple independent laboratories, as well as instruments such as GPI [14], P1640 [15] and SCExAO [16], [17]. The two techniques used at the ACE laboratory are the Electric Field Conjugation (EFC) [18] and speckle nulling (SN) [19].
EFC is fast and has the ability to measure the incoherent light in the system but is dependent upon the accuracy of the optical model of the system. On the other hand, SN, although significantly slower, is more robust. Both algorithms allow us to reach the requirement from 1.1 to 3.6 \( \lambda/D \) (on the sky). However, the region from 3.7 to 4 \( \lambda/D \) (on the sky) falls close to the outer range of the MEMS DM’s control area and the EFC algorithm has issues reconstructing the wavefront and therefore struggles to create the proper dark zone. One potential explanation is that the algorithm shifts the center of gravity of the PSF leading to sampling errors in the model. Other potential modeling errors is non-identified discrepancies between the model and the actual layout, or that our model of high spatial frequencies is not as good as for low frequencies. This is still an on-going area of investigation.

3 Instabilities control

In addition to having a thorough calibration, we also need to reduce instabilities. Instabilities come from different areas including: mechanical, optical and simulation errors (mostly in the case of EFC). To control temperature, our layout is located inside an active thermal enclosure that provides excellent stability of \( \leq 1\text{mK} \) rms over \( \approx 30 \text{ minutes} \). It is designed to stabilize temperature-induced dynamic tip/tilt errors and air motion. This enables EXCEDE contrast performance without resorting to vacuum. Also, both the science camera and the LOWFS camera are actively cooled. Furthermore, the LOWFS corrects for tip/tilt and PSF drifts. The correction is sent in closed loop to the entrance fiber, before the PIAA. We independently measured the modes upstream and downstream of PIAA and the upstream modes (including PIAA M1) are an order of magnitude stronger. From the LOWFS measurements, no information is currently sent to the MEMS DM but this will be done in the near future.

Other aberrations, mostly of high temporal frequency, will limit our achievable contrast since the randomly spread the light over the dark region of interest. This diffracted light will change rapidly. In order to reduce the turbulence impact on our images, we installed additional beam baffling to decrease some of the sporadic instabilities seen at both small and larger separations. Another techniques we use to complement the baffling is lucky imaging. For each iteration, we take between five and ten images per probe and only use the one image per probe with a contrast higher than a given threshold to measure the wavefront. This lucky imaging techniques works well except for mid-temporal frequency aberrations. Note though that this procedure was not necessary to meet the milestone.

We can reduce the impact of instabilities by working at low intensity which leads to long enough exposures that average fast instability that EFC (mainly) or speckle nulling would otherwise try to track and correct.

4 Laboratory results

4.1 Contrast achieved

Figure 4 shows the final results using speckle nulling. The best median contrast achieved is \( 4.35 \times 10^{-7} \) between 1.2 and 2 \( \lambda/D \) simultaneously with \( 7.98 \times 10^{-8} \) between 2 and 4 \( \lambda/D \). The mask was positioned at an inner working angle of 1.12 \( \lambda/D \). Figure 4-left shows an average of 1500 images taken over an hour. The contrast is slightly below our maximum achievable contrast because of instabilities but still comfortably below the milestone requirements.
Angle $\lambda/D$

Angle $\lambda/D$

mean: $7.03 \times 10^{-7}$, median: $4.06 \times 10^{-7}$, 1.2 – 2.0 $\lambda/D$

mean: $1.99 \times 10^{-7}$, median: $8.51 \times 10^{-8}$, 2.0 – 4.0 $\lambda/D$

Fig. 4. Left: Average contrast measured over an hour. Right: Instantaneous average and median contrast over an hour (1500 measurements). The average median contrast achieved for this run is $4.1 \times 10^{-7}$ between 1.2 and 2 $\lambda/D$ simultaneously with $8.5 \times 10^{-8}$ between 2 and 4 $\lambda/D$.

Once the dark zone achieved, the system is very stable as shown in Figure 4-right. The contrast stays under $10^{-6}$ in the inner region and under $10^{-7}$ in the outer region for over an hour (represented using 1500 images). We also ran three independent tests that reached the same performance.

4.2 Incoherent light

The light coming from the planet is incoherent from the light originating from the star. EFC enables us to measure the level of incoherent light and use it to better understand our current limitations. If the model is correct, subtracting the reconstructed image $|E_{\text{recon}}|^2$ from the measured intensity $I_{\text{meas}}$, one obtains the residual light $I_{\text{inc}} = |E_{\text{recon}}|^2 - I_{\text{meas}}$. The quantity $I_{\text{inc}}$ represents light that cannot be removed by the MEMS. This residual incoherent light comes from ghosts in the system, fast image instabilities that makes the correction obsolete, and model errors.

Figure 5 shows the incoherent light in our system. The main errors are close to the core where the image suffers from high temporal frequency instabilities, and on the outer edge where our model is less robust. The amount of light in these regions ranges from 1 to $3 \times 10^{-7}$. Outside these regions, the incoherent light introduces contrast errors below $10^{-8}$.

5 Conclusion and future work

Over the past year, tremendous progress has been made at the ACE laboratory in terms of stability control over the past year. These improvements allowed us reach $10^{-6}$ raw contrast between 1.2 and 2.0 $\lambda/D$ and $10^{-7}$ raw contrast between 2 and 4 $\lambda/D$. Moreover, the lessons learnt will serve for high contrast imaging at small separation using ELTs [20]). In particular, stability is very important at small separations and might be one the main limiting factors with ELTs. Correcting for instabilities will be challenging and will require special care. Finally, our next steps are to run the same tests under vacuum and to optimize the technique for broadband light.
Fig. 5. Measurement of the incoherent light $I_{inc}$

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