OBSERVING REQUEST
University of Arizona Observatories

ENG 292

Year: 2015 **Term:** Jan–Jul **Proposal type:** engineering*

On-sky validation of the highly sensitive non-linear curvature wavefront sensor (nlCWFS)

P.I.: Olivier Guyon (SO; *oliv.guyon@gmail.com*; 818 293 8826)

CoI(s): Michael Hart (SO), Johanan Codona (SO), Mala Mateen* (Optical Sciences + SOR), Don McCarthy (SO), Laird Close (SO), Jared Males (SO)

Abstract of Scientific Justification

The non-linear curvature wavefront sensor (nlCWFS) is a high-sensitivity alternative to conventional wavefront sensors for adaptive optics, operating at the sensitivity limit imposed by the full telescope aperture diffraction limit. We are requesting two well separated 1/2 night observing runs to continue development of the nlCWFS. Our early nlCWFS prototype (used on MMT in 2013) has undergone major redesign and improvement and is now capable of imaging simultaneously out-of-focus stellar images in multiple conjugation planes in 3 broadband colors. This new approach was demonstrated for the first time during our March 11, 2014 engineering night on MMT. With further improvements to the nlCWFS hardware and software, we are now capable of acquiring both snapshot data (using a common shutter) and video-rate images, providing the multi-conjugation multi-color dataset which is essential to (1) optimize the design (location of imaging planes) of future sensors of this type and (2) test and validate wavefront reconstruction algorithm (a subset of the images can be used to reconstruct the other images). Simultaneous SHWFS data will also be acquire to quantify the on-sky sensitivity gain offered by this new approach. This work is supported by a NSF ATI grant and is now entering its final year.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling: Optimal	Scheduling: Acceptable	Sharing: Poss.	Sharing: Adv.
1	MMT	f/15	AO+nlCWFS+ARIES	*	*	0.5	bright	Feb-Mar	Jan-Jul	yes	yes
2	MMT	f/15	AO+nlCWFS+ARIES	*	*	0.5	bright	May-Jul	Jan-Jul	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: Unusable dates: Jan 1-10, Jun 21-27

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A * appended to the proposal type indicates a continuation proposal; a * appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a * appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	Bright star, low airmass			$V \approx 6$, low airmass
2	Bright star			$V \approx 6$, airmass ≈ 1.5
3	Fainter star			$V \approx 10$, low airmass

Approval for Instrument Use from PI: See attached e-mail from Don McCarthy

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
			no	no

Scientific Justification

The need for better wavefront sensing sensitivity. Wavefront sensors are the fundamental limit to adaptive performance: regardless of technology improvements in deformable mirrors, wavefronts can only be corrected as well as they are measured. While technology (computers, optics) continuously improves the performance of such sensors, they are fundamentally limited by photon noise. This limit is especially important for "extreme-AO" systems running at high speed with many actuators, and aimed at high contrast imaging of exoplanets and disks around nearby stars, but also affects most other AO systems. There is therefore a strong scientific motivation to improve wavefront sensors sensitivity, which is defined as the efficiency with which photons are used to measure phase aberrations.

The non-linear curvature wavefront sensor (nlCWFS) concept (Guyon, PASP, 122, 2010) was developed to improve wavefront sensing sensitivitity, and relies on simultaneous imaging of the telescope beam in different conjugation planes to measure the wavefront map. It was developed to combine the two most desirable fundamental features of a wavefront sensor: (1) it is highly sensitive, operating at the diffraction limit of the telescope, and (2) it can measure large wavefront excursions, and is therefore able to measure the full atmospheric turbulence as visible wavelengths where sensitivity is optimal and fast low-noise detectors are available. No other sensor offers such theoretical performance: conventional SH-type sensors can measure large wavefront excursions but with poor sensitivity, while interferometer-type WFSs can offer high sensitivity but cannot measure large wavefront errors. The Pyramid wavefront sensor offers an advantageous compromise, and would reach full sensitivity with no modulation (but would then be limited to measuring nearly flat wavefront). The price to pay for achieving both sensitivity and large dynamical range is non-linearity: for wavefront errors above ≈ 1 radian, the relationship between wavefront map and intensity signal in the WFS is non-linear, requiring specific non-linear wavefront reconstruction algorithms to be used for reconstruction, as shown in Guyon 2010.

Project history and current status of nlCWFS work. We have designed and assembled two nlCWFS prototypes on the MMT AO system. Our first prototype fed four beams to a single high speed camera. The major innovation for this sensor (relative to the original concept) was to split the four beams according to wavelength, therefore considerably reducing the chromaticity issue. While this prototype demonstrated that the approach is suitable to build a nlCWFS, it proved difficult to align and operate due to the large number of small size optics in the optical train. It was first used on-sky in Sept 2013, and, despite significant hardware/optical issues, captured starlight. During our second run (Dec 2013), we successfully demonstrated simultaneous high speed acquisition of 3 out of the designed 4 beams (optical alignmnent prevented us from imaging all four beams). We have since built a 2nd prototype using experience from the 1st prototype. This second system uses a more widely separated dichroic splitting layout feeding individual cameras: it is thus more flexible and is considerably easier to align. The design is also easily scalable (cameras can be added). The goal of this second system is somewhat different than the first system: we now need to image a larger number of planes and wavelengths to better evaluate the optimal location of the planes and the effect of residual chromaticity. We therefore chose to use separate color cameras (4 cameras) to obtain 12 independent Fresnel numbers (4 planes x 3 wavelengths). The prototype was built and deployed on the MMT, and had first light in March 2014.

Measurements goals. Our core goals for the project are to (1) understand how chromatic effects and number and location of imaging planes affect the nlCWFS reconstruction quality and (2) demonstrate that the reconstruction of the WF with high accuracy can be achieved sufficiently fast for on-sky nlCWFS close loop operation. To achieve these goals, we must acquire a data set of sufficient quality and redundancy to allow independent verification that the reconstructed solution is correct, with the wavelength and conjugation diversity to explore and quantify the reconstruction performance as a function of key design choices (spectral bandwidth, number and location of planets). Together, these results will establish the feasibility of the nlCWFS and allow AO system designers to adopt and design the nlCWFS. Our multi-camera nlCWFS system is now ideally suited to make this measurement. Following the March 2014 demonstration, we have been upgrading the nlCWFS hardware and software, and have been addressing issues that limited our data quality and collection efficiency, and we are therefore requesting engineering time to acquire the polychromatic multi-conjugation on-sky dataset.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

We will use our second nlCWFS prototype (shown in Figure 1) for these observations.

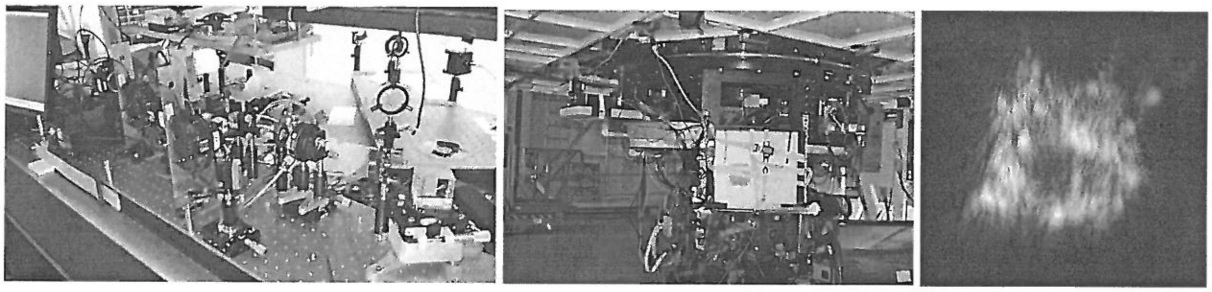

Figure 1: Second nlCWFS prototype, to be used for the proposed observations. Four individual cameras (left) campure 12 Fresnel planes simultaneously. All hardware is mounted on an optical breadboard that is mounted on the side of the MMT top box (center). A sample short exposure raw image, acquired in Dec 2014 with one of the four cameras, shows the diffraction-limited speckles used for the high sensisitivity wavefront reconstruction. Strong chromatic effects, due to both atmospheric refraction and chromatic beam propagation, are visible.

MMT AO wavefront sensor telemetry will be acquired simultaneously with nlCWFS data. This is essential to allow direct comparison of the two wavefront sensors, and will allow wavefront reconstruction algorithms for the nlCWFS to be tested against SH WFS measurements. We plan to image PSFs with ARIES during nlCWFS tests, so that wavefront measurements can be tested against focal plane images. While ARIES will not acquire images at sufficiently fast frame rate to resolve atmospheric speckles, long exposure PSFs can be reconstructed using nlCWFS data and compared with ARIES images. A narrow-band filter will be used in ARIES to avoid saturation when bright stars are observed.

Our targets will include stars between $m_V \approx 6$ and $m_V \approx 10$. The faint magnitude limit for the nlCWFS will be explored primarely by adding noise to the raw data in post-processing, but also by slowing down the MMT AO loop to produce partial correction conditions. While we will mainly observe targets at high elevation, we will also collect data on higher airmass target(s) to quantify the effect of atmospheric dispersion.

While we strongly prefer to use ARIES for PSF monitoring, we can mount and align a flat mirror at the back of the telescope to direct light the MMT AO WFS if ARIES is not available. We note that this scheme was employed in Sept 2013 to collect on-sky data, although it was poorly planned and executed (a proper mechanical interface and larger mirror were since manufactured to solve this issue), resulting in poor data quality.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in.* ***(up to one page)***

Previously awarded time: Three engineering nights have been allocated to this project on MMT, each leading to substantial improvement in our hardware and data collection strategy: Sept 19, 2013, Dec 12, 2013 and March 11, 2014.

We have significantly improved the nlCWFS system, which is now able to acquire a rich dataset of showing how our-of-focus speckles evolve as a function of both color and conjugation. This dataset is essential to understand and quantify fundamentals of the nlCWFS approach. We request two half nights to acquire this dataset. It is important for our team to have two well-separated runs in order to leave time for potential system improvements between the runs. For each of the two runs, a half night will be sufficient to collect data on a few bright stars.

The nlCWFS activity is led by our UofA group, and includes collaborators at other institutions: Jean-Pierre Veran (NRC, Canada) and Carlos Correia (University of Porto) are developing wavefront reconstruction algorithms for the nlCWFS; the StarFire Optical Range group is also investigating nlCWFS implementation for military use. All data collected will be made available to these groups and collaborators.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). **(up to one page)***

⋆ Sept 19, 2013 (1 engineering night on MMT). Some data collected with first prototype, but of limited use. Several technical issues were identified, and addressed prior to the Dec 2013 run.

⋆ Dec 12, 2013 (1 engineering night on MMT). First successful data acquisition on a single high speed camera with a multi-color beam splitting approach. We experienced difficulty in establishing and maintaining alignment of all beams at the telescope.

⋆ March 11, 2014 (1 engineering night on MMT). First light for prototype 2. 12 Fresenel planes (3 colors x 4 conjugations) were simultaneously imaged. Major characteristics of images were identified (chromaticity due to atmospheric refraction, beam propagation effects) leading to improvements in the instrument design and data acquisition plan, to be applied for the two proposed runs.

Johanan Codona <jlcodona@gmail.com>

email of support from ARIES

Don McCarthy <dwmccarthy@gmail.com> Tue, Sep 30, 2014 at 10:29 PM
To: Olivier Guyon <oliv.guyon@gmail.com>
Cc: Johanan Codona <jlcodona@gmail.com>, Craig Kulesa <ckulesa@as.arizona.edu>

Hi Olivier,

We are happy to collaborate in your proposal to use ARIES with nlcWFS.

Please note that we cannot provide ARIES after mid-May.

Don

On Tue, Sep 30, 2014 at 6:56 PM, Olivier Guyon <oliv.guyon@gmail.com> wrote:

> Don,
>
> Here is a copy of our proposal.
> Could you please email us a statement of support as you did last year ?
>
> Thank you,
>
> Olivier