Advanced Wavefront Sensing and Control Testbed (AWCT)

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ABSTRACT

The Advanced Wavefront Sensing and Control Testbed (AWCT) is built as a versatile facility for developing and demonstrating, in hardware, the future technologies of wavefront sensing and control algorithms for active optical systems. The testbed includes a source projector for a broadband point-source and a suite of extended scene targets, a dispersed fringe sensor, a Shack-Hartmann camera, and an imaging camera capable of phase retrieval wavefront sensing. The testbed also provides two easily accessible conjugated pupil planes which can accommodate active optical devices such as fast steering mirror, deformable mirror, and segmented mirrors. In this paper, we describe the testbed optical design, testbed configurations and capabilities, as well as the initial results from the testbed hardware integrations and tests.

Key words: wavefront sensing and control, active optics, phase retrieval, Shack-Hartmann sensor, dispersed fringe sensor, deformable mirror, segmented mirror, space telescopes, ground telescopes

1. INTRODUCTION

As modern astronomy demands ever increasing size of telescopes for both space and ground based astronomical observations, people have to resort to use the smart structure and active optics to meet the tight requirements for large optics performance. Light weighted mirrors, segmented mirrors, and shape controllable mirrors are used instead of single rigid well polished mirrors. This approach will not only maintain the primary mirror optics size to be manageable by the fabrication process or launch vehicle packaging but also reduce the cost and schedule. However, to achieve the required optical performance these types of large telescopes will rely on active optics to align, phase, control, and maintain the telescope optics so that they provide astronomers a diffraction limited telescope. A key component of an active optics system is the wavefront sensing and control (WFSC), in which the wavefront sensors accurately measure any optical wavefront error due to the misalignment or environmentally induced drift while a feedback control system uses rigid body actuators, mirror shape actuators, or other active control mirrors to compensate this wavefront error.

Advanced Wavefront Sensing and Control Testbed (AWCT), funded by JPL’s internal research and technology development (R&TD) grant, has been built to provide a versatile testbed for further development of the wavefront sensing and control technology. The intent for this testbed is to support JPL wavefront sensing technology development for future projects, improve the current WFSC algorithms, create and test new ideas of WFSC, and provide hands on training on WFSC for both JPL and collaborating institutes.

AWCT is a self contained testbed which has two large format (4k X 4k pixels) CCD cameras for wavefront sensing and a source module that is able to project either a point source or an extended scene image into the testbed. Of the two CCD cameras one is a dedicated Shack-Hartmann camera (SHC), while other is an imaging camera on a linear translation stage which is ideal for imaging based wavefront sensing such as phase retrieval camera (PRC) and dispersed fringe sensor (DFS). There are two conjugate pupil planes with different sizes on AWCT which are ideal for accommodating various wavefront correction devices such as deformable mirror (DM), actuated segmented mirrors, or fast steering mirror (FSM). The spacious layout of AWCT optics also makes configuration changes possible and has potential for expansion or modification for testing other optical subsystems.
After having finished its optical and electronic integration, optical alignment, and initial wavefront testing the AWCT recently has begun its wavefront sensing and control experiment phase. In the following section we will describe the testbed optical design and highlight the functions and capabilities of each AWCT sub-system. In Section 3 we will present some preliminary wavefront sensor experimental data and results. Section 4 summarizes our plans for the next WFSC tests and some future ideas we have for this testbed. Hopefully this will bring out more ideas and form a few collaborations in the future.

2. AWCT TESTBED DESCRIPTION

2.1 Optical layout overview

Figure 1 shows the optical layout of AWCT. The testbed optics consist of the source module, the source projection optics (SRC), the pupil relay optics, the phase retrieval camera (PRC) optics including dispersed fringe sensor (DFS), and the Shack-Hartmann camera (SHC) optics. Figure 2 is a picture showing the AWCT.

![Optics layout of AWCT](image)

Figure 1. Optics layout of AWCT which shows the source projection optics (down and to the left side of optical trains, after the Source BS), the pupil relay optics (middle lower, between the Fold Flat and the Return Flat), the PRC optics (middle optical train, right of the PRC BS), and the SHC optics (upper optical train, beyond the Source BS).

The AWCT optics are designed for broadband visible light imaging ($\lambda = 500 – 900$ nm). The system utilizes optical mirrors, lenses, and broadband beam splitters. The four lenses for the source, PRC, and SHC in AWCT are air spaced triplet lenses with similar designs. The design satisfies the required focal length for imaging and minimizes design aberration both for the field of view and wavelength bandwidth. The AWCT optics design is diffraction limited over the entire field of view and wavelength bandwidth of PRC and SHC. The AWCT’s system pupil is defined at Fold Flat and is located in the collimated beam path. Images on both PRC and SHC cameras are critically sampled for the mid-wavelength ($\lambda = 700$ nm).

Light from either the point source or the extended scene target, selected by a flip-in Source Select Mirror (Src Select Mirror), is collimated and projected by the Source Lens into the AWCT optics through the Source Beam Splitter (Source BS). After passing through another beam splitter (PRC BS) the source light comes to the system pupil stop defined by a 37 mm diameter mask on the Fold Flat. The pupil Relay Optics consists of three off-axis powered mirrors (RM1, RM2, RM3) in a TMA configuration. The relay optics re-images the pupil at the Fold Flat onto the Return Flat with a 4X pupil magnification. With two accessible pupil planes of different sizes the testbed can accommodate various wavefront correction devices. It is our intention to replace the Fold Flat with a DM and the Return Flat with an
assembly of segmented mirrors. The light retro-reflected back from the Return Flat passes through the Relay Optics and the Fold Flat a second time. At the PRC BS half of the returned light will be reflected to the PRC camera. The PRC Lens is a triplet lens identical to the Source Lens. It focuses the image light and forms a telecentric pupil for the PRC camera. The returned light that is transmitted through the PRC BS and Source BS continues into the SHC optics. The first SHC Lens (SHC Lens1) focuses the image light and a field stop (SHC Field Stop) is placed there to prevent any cross talk between the neighboring subapertures (see Figure 8) on the SHC. The second SHC lens (SHC Lens2) then collimates the light and forms a pupil onto the SHC lenslet array which is placed before the SHC CCD detector. SHC Lens1 and SHC Lens2 are identical and they form a one-to-one image of the system pupil on the SHC.

More detailed description of the functions and designs of each sub-optics system will be given below.

2.2 Phase Retrieval Camera (PRC)
Optics for PRC path includes the PRC BS, the PRC Lens, and the PRC CCD camera (Figure 1). The PRC BS is a custom made 50% broadband beam splitter (BS). The PRC BS contains a wedge to separate the PRC BS ghost from the main point source even at the largest defocus because the phase retrieval algorithm is very sensitive to any optical ghosts. The imaging lens for PRC is an air spaced triplet design which forms a diffraction limited image over the entire field of view of the PRC CCD for all broadband visible wavelengths between 500 nm – 900 nm. The PRC Lens focuses the collimated light from the pupil (Fold Flat) to form an F/25.7 focused beam on the PRC CCD detector. The F/# is chosen to have the image critically sampled (Q = 2) by the CCD pixels (pixel size 9 x 9 μm) at the center wavelength of 700 nm. The PRC Lens also images the pupil to infinity, forming a telecentric system for the PRC camera. Thus, movement of the PRC camera in and out of focus results in a constant PRC image scale. This simplifies the image processing for the phase retrieval algorithm. The phase retrieval application of the PRC camera requires the camera to take out of focus point spread function (PSF). For this the PRC camera is mounted on a linear stage with the travel direction aligned with optical axis. The 100 mm travel range of the stage provides the equivalent of ±13.5 waves of defocus for the PRC camera. The PRC can also be used as a Science Camera when it is used for in focus imaging. The PRC camera is a CCD camera with 4k by 4k pixels (16M pixels total) and each square pixel is 9 μm X 9 μm in size. The PRC camera uses a Kodak KAF-16801 chip and it is a modified version of 800 Series Camera from Spectral Instruments, Inc. The camera has a full well of 90,000 e⁻ and read out noise about 13 e⁻. Besides imaging the source there is a flip-in doublet lens which forms a pupil image on the PRC camera (Figure 1). The pupil image captures the pupil illumination distribution and, when working with other devices at the pupil plane, the actual geometric shape of the pupil for phase retrieval algorithm.
Depending on the source selected, the PRC can be used for either the point source imaging or the extended scene imaging. While the defocused point source PSFs are used for phase retrieval, a defocused extended scene from PRC can be used for field diversity wavefront sensing which retrieves both the wavefront phase and image \[^8\].

### 2.3 Dispersed Fringe Sensor (DFS)

With a flip-in dispersion grism and broadband point source the PRC camera can also be used as a dispersed fringe sensor (DFS) (Figure 1). The DFS grism disperses broadband light and forms a spectrum on the PRC detector. DFS uses modulation in the dispersed broadband spectrum to sense the wavefront pistons and it is a powerful sensor for phasing segmented mirrors \[^4\]. The AWCT’s DFS consists of a flip-in grism assembly behind the PRC Lens. The grism, with a groove frequency of 75 line/mm, creates a dispersion spectrum with wavelength dispersion of 0.13 nm/pixel over the entire AWCT’s visible band. The grism is mounted on a rotational stage which can change the grism’s dispersion direction in 360º with accuracy of 0.01º. The variable dispersion orientation enables the DFS to provide optimal fringe contrast needed for any segments geometry orientations \[^5\]. The DFS wavelength dispersion calibration is done by narrowband imaging with the DFS at different center wavelengths. This is achieved by selecting the narrow band filters in the source module (see Section 2.5.)

### 2.4 Shack-Hartmann Camera (SHC) and Extended Scene SHC (ESHC)

The AWCT’s SHC optics consists of a pair of identical triplet lenses, a fold flat, a field stop, and a lenslet array (Figure 1). The SHC Lens1 forms a real image which allows the use of the SHC Field Stop to limit the field of view in SHC camera so that light for each subaperture will not spill over to its neighboring subaperture. The SHC lenses also relay the system pupil to the SHC lenslet array. Since the SHC lenses are identical the pupil formed will be the same size as the system pupil (\(D = 37 \text{ mm.}\)). The SHC lenslet array currently installed on the AWCT’s SHC has about 110 subapertures across the pupil, with total about 10,000 lenslets. The pupil sampling density is mainly driven by the desire to have more spatial resolution of the wavefront to be measured. Lenslet arrays with different pupil sampling are also available for AWCT. The lenslet array is arranged in a hexagonal pattern and each lenslet has an aperture size of 0.325 mm. The lenslet lenses have the same F/25.7 which ensures the critical image sampling for the 9 \(\mu\)m pixel \((Q = 2)\). A critically sampled design is selected to maximize the image field content. Due to the short focal length of the lenslets, the lenslet array is used as a SHC CCD camera window and the focal length of the lenslet is controlled by a spacer between the lenslet array substrate and the CCD chip. The SHC CCD camera has the same Kodak 4k x 4k chip as the PRC and the camera is also a modified 800 Series Camera by Spectral Instruments, Inc. With the current lenslet array each SHC subaperture has about 36 X 36 pixels. The SHC can be used with the point source where each subaperture wavefront slope is calculated by the centroids of the PSF. When used with extended scene target, each SHC subaperture lenslet forms its own image of the target (Figure 8) and the subaperture wavefront slopes is calculated by the image cross-correlations. Our extended scene Shack-Hartmann wavefront sensing algorithm is based on a smart image correlation method \[^6\].

### 2.5 Source optics and source module

The AWCT has a versatile source optical subsystem which provides the testbed with either an on-axis point source or an extended scene image which fills up the camera detector (Figure 1.) A source select mirror (Src Select Mirror in Figure 1) allows the testbed to be in either the point source imaging mode (Src Select Mirror out) or the extended scene imaging mode (Src Select Mirror in.) The point source and the extended scene target are conjugated at the focal plane of the source projection lens (Source Lens). The Source Lens collimates the light from source and projects it into the AWCT system pupil. The Source Lens is a triplet lens identical to the PRC Lens, thus the testbed forms a one-to-one scaled image on the PRC camera.

The point source is launched from a single mode fiber (SMF). With a source projection lens at F/25.7 the SMF source creates a reasonably flat illumination at the pupil plane. The amplitude droop measured with PRC pupil imaging lens is less than 10% (Figure 5.) If more uniform pupil illumination is desired a pin-hole can replace the single-mode fiber as the point source.

There are 5 transparent scene targets used for AWCT. They are 4 Air Force targets, with different resolution groups and reversed background, and an aerial picture of JPL. These targets, 2 inches in diameter, are mounted on a 5-position filter wheel which allows the user to remotely switch scenes during the experiment. The transparent extended scene target is
illuminated by the light diffused by a holographic diffuser and then the ground glass on the other side of the target substrate. A multimode fiber (MMF) provides the broadband light for the target illumination.

The point source SMF and the extended scene illumination MMF deliver light into the AWCT optics from the source module. The source module is located next to the AWCT optics and enclosed by its own panel box (Figure 2, right). Figure 3 illustrates the optical layout for the source module. The AWCT light source is a commercial super continuum (SC) source which provides high power (max 2.2 Watt) broadband light with wavelength range from 457 nm to 2000 nm. The output power of this SC source can be controlled via a USB port. The output of SC light, conducted via an optical fiber, is collimated. It first goes through an IR filter to remove unwanted IR radiation. After the IR filter the maximum power is about 0.4 Watt with wavelength cut off beyond 900 nm. It then goes through an 8-position filter wheel which contains various neutral density (ND) filters. This allows a discrete control of source light intensity. After the ND filter the broadband light is split to two paths by a beam sampler plate. A small portion of it (~4%) is reflected off the beam sampler for the point source and rest of light is fed into the multimode fiber by a 10X microscope objective lens for the extended scene source. The uneven split ratio considers the fact that light for the extended scene target needs to be diffused and then observed by many small lenslets which cover the entire CCD chip, while the light for the point source will be mostly focused onto a small region of CCD even with defocus. The light for the point source also goes through a wavelength filter wheel which contains either no filter (broadband light) or various narrow band filters before being focused into the single mode fiber by a 20X microscope objective lens. The narrow band filters are used for the PRC phase retrieval measurements as well as the wavelength dispersion calibration for the DFS. Each arm of the source contains a shutter which can be used for selecting either the point source or extended scene source, or for taking dark images without disturbing the settings on the super continuum source. The shutters are controlled by the testbed computer via a RS232 serial port.

![Figure 3. Illustration of the AWCT source module optical layout.](image)

***2.6 Wavefront correction devices for AWCT***

The AWCT is designed to accommodate various wavefront correction devices using its two easily accessible pupil planes, one is at the Fold Flat with pupil size of $D = 37$ mm and the other is at the Return Flat with equivalent pupil size of $D = 148$ mm. Currently in our test we have a 97-actuator deformable mirror, a 32 x 32 high density deformable mirror, and a 3-segment mirror available for us to do the WFSC experiment on AWCT.

The AWCT optics spread out on a large commercial optical table with pneumatically isolating legs. The subsystems, such as PRC, SHC, and SRC, are all coupled together with collimated beams. This makes the change of optical configuration or the testbed upgrade reasonably easy. When needed we can retrofit the testbed to a different configuration to test other optical components, assemblies, or wavefront sensing and correct subsystem.

**2.7 AWCT electronics, software, and computer**

The AWCT uses the commercial off the shelf (COTS) devices and controllers. The CCD cameras have the Fiber Link interface and all other devices have a serial port supporting either RS232 or USB interfaces. Whenever available we try to use the commercial software provided by device vendors to drive the devices. We have developed a simple GUI to control the supper continuum source intensity, source shutters, and filter wheels. All the device control software runs on
3. AWCT INTEGRATION AND INITIAL TEST RESULTS

3.1 The AWCT integration, alignment, and the interferometer measurement

A high accuracy coordinate measurement machine (CMM) from FARO and an instantaneous phase shifting interferometer from ESDI are used for AWCT optical integration and alignment. Depending on the size and shape of optics the CMM can place the optics accurately within ±5 - 15 μm in translation and ±5 - 10 arcsec in rotation relative to the designed position. While the CMM can place the optics to their designed position mechanically with high accuracy the optics still need to be aligned optically using the alignment interferometer in order to achieve their optimum optical performance. The AWCT optical alignment is done with the ESDI interferometer. During the AWCT alignment the interferometer replaces the Return Flat, projecting the collimated measurement beam into the AWCT optical train. A Zygo beam expander expands the collimated beam of interferometer to 6" in diameter so that the full aperture of the AWCT is measured during the optical alignment. The optics are aligned one at a time starting with the RM1 and the entire AWCT optical train is gradually built up from there. During the optical alignment a reference flat or a reference spherical mirror is used to retro-reflect the measurement beam back to the interferometer. At each step the aligned optics are tweaked in tilts and/or translations to minimize the wavefront measured with the interferometer. For the AWCT our final post-alignment wavefront error is measured 30.2 nm RMS for the PRC optical path and 29.1 nm RMS for the SHC optical paths. This post-alignment wavefront error is measured in “double-pass wavefront”, i.e. the interferometer measurement beam passes through the optics twice because the retro-reflecting reference has to return the beam back to the interferometer. The dominant post-alignment wavefront error is the astigmatism caused by the residual alignment error in the Relay Optics (RM1 – RM3). Figure 4 shows the post-alignment interferometer OPD maps for the PRC and the SHC optical paths. When the alignment of the PRC, the SHC, and the Source paths are done with the interferometer the Return Flat mirror is put back in and its alignment was done using the CMM and the PRC camera.

![Interferometer OPD: PRC](image1)

![Interferometer OPD: SHC](image2)

Figure 4. The double-pass wavefront errors (OPD) measured by the alignment interferometer. The OPD on the left is from the PRC optical path. A convex reference mirror is placed behind the PRC lens to retro-reflect the measurement beam back to the interferometer (Figure 1). The OPD on the right is from the SHC optical path. A flat reference mirror is placed at the SHC to retro-reflect the measurement beam from the SHC camera back to the interferometer. The distance of the SHC optical path from the alignment interferometer is much longer than that of the PRC therefore the measurement will suffer more of the air turbulence.

With the AWCT testbed integration and alignment finished the testbed has now begun the WFSC test phase. In following sections we will present some initial test results from the PRC and the SHC. The test results from the DFS will be presented in a separate paper in this conference [7].
3.2 PRC data and results
The plots in Figure 5 show an example of the PRC phase retrieval data which are used to measure the AWCT’s as-built wavefront quality. A typical PRC phase retrieval dataset consists of a few defocused narrowband (with a 635 nm diode laser in this case) point source PSFs and an image of pupil taken with the Pupil Lens (Figure 5.) The defocused PSFs are analyzed by our Modified Gerchberg-Saxton (MGS) phase retrieval algorithm to get the wavefront map (OPD), which is shown in Figure 6.

Comparing the OPD measured by the interferometer (Figure 4, left) and that by the PRC (Figure 6) we can see that they agree with each other very well both in terms of RMS WFE and in the shape of OPD map. Notice that compared with the interferometer measurement the PRC’s OPD is rotated. This is because the PRC camera, hence the wavefront measurement coordinate, is mounted with a 17.5 degree rotation relative to the XY coordinate of the interferometer. Both OPDs contain the same dominant wavefront error of astigmatism which is from the residual alignment error in the Relay Optics. The other subtle differences between these two OPD maps are probably due to: (a) the air turbulence; (b) the Return Flat mirror surface error which was not present in the interferometer measurement; (c) the wavefront difference between the Source Lens and the PRC Lens caused by fabrication and alignment.

Figure 5. The PRC phase retrieval data. From left to right the defocus value of -11.1, -5.6, +5.6, and +11.1 waves ($\lambda = 635$ nm) are introduced using the linear stage under the PRC camera. The last image on the right is the pupil image from the PRC camera taken with the Pupil Lens flipped in. The mirror mounting tabs on the Return Flat are visible and in-focus because the Return Flat is conjugated with the system pupil.

Figure 6. The PRC phase retrieval result. In the measurement the optics includes the Source Module optics, the Relay Optics (double pass), and the PRC optics. Since the PRC lens and the Source Lens are identical the PRC OPD map can be compared to the interferometer’s double pass OPD shown on the left of Figure 4.
Figure 7 shows an example of the PRC in the extended scene imaging mode. Here a negative Air Force target (Scene #2) is illuminated with the broadband source. The PRC camera focus is changed by the linear stage. The in-focus and the defocused images of the extended scene target can be used for retrieving both the wavefront and true image [8].

3.3 The SHC data and results

Figure 8 is the SHC image on an extended scene target (Scene #4.) On the left is the full SHC image (4k X 4k pixels). The image illustrates the coverage of SHC subaperture over the system pupil. Each “dot” is an SHC subaperture image. On the right is a zoomed-in view which shows more details of the extended scene image formed by the SHC subapertures. All the AWCT extended scene SHC images are broadband images.

Figure 8. The SHC image on an extended scene target (Scene #4). On the left is the full frame SHC image which shows the pupil being sampled by many SHC subapertures. On the right is a zoomed-in view which shows the details of a few subaperture images. The boundary of each subaperture field of view is defined by the size of the SHC Field Stop.
When imaging with the point source it is very hard to display the full SHC image in the plot because of the resolution limitation of the publication, so here we present only the zoomed-in view in Figure 9. For the point source the SHC image can be broadband or narrow band depending on the wavelength filter selected. The point source SHC image shown in Figure 9 is of a narrow band ($\lambda = 635$ nm.)

Figure 9. A zoomed-in view of the point source SHC image. The X and Y axis labels show the pixel range of the image displayed. In the point source SHC mode each subaperture still has the same number of pixels and field as that of the extended scene SHC mode (limited by the SHC Field Stop). This gives the point source SHC a very large wavefront aberration capture range.

Unlike PRC the SHC does not measure wavefront phase directly. Instead it measures the wavefront slopes across each subaperture and from these local slopes a wavefront OPD map is reconstructed. For the point source SHC the subaperture slopes are measured by the PSF centroid offset from the ideal PSF location. To calibrate this ideal PSF location we placed a single mode fiber at the center (using the CMM) of the SHC Field Stop and used the SHC Lens2 to create an “ideal” wavefront for the SHC. Of course the wavefront generated by the SHC Lens2 also contains the wavefront aberration from the lens itself. But a separate interferometer test on the lens has shown that the lens quality is very good with the wavefront error measured to be less than 10 nm RMS. Therefore the calibration is a close representation of the ideal wavefront.

Figure 10 shows the SHC wavefront measurement (OPD) from the point source SHC image (Figure 9). The measured wavefront error is 23.9 nm RMS. Like the PRC and the interferometer measurements the dominant wavefront error seen by the SHC is the astigmatism caused by the residual alignment error in the Relay Optics.

Figure 10. The point source SHC wavefront measurement OPD result. In this measurement the optics includes the Source Module optics, the Relay Optics (double pass) and the SHC optics. The shape of the SHC OPD resembles that of the PRC OPD except it is rotated by 180 degrees.

It is interesting to compare the shape of the SHC OPD against that from the PRC. Their shapes resemble each other with the exception of a 180 degree rotation between them. The 180 degree rotation is due to the reimaging of pupil by the
The PRC and SHC optical train are very similar with the exception that the SHC has one more lens compared with PRC. So the resemblance of their OPDs is not surprising. Furthermore the PRC and SHC resemblance agrees with our diagnosis of the dominant wavefront error is from the Relay Optics residual alignment error because the Relay Optics, measured in double pass, is common to both the SHC and the PRC. However the resemblance is less so when comparing the SHC OPD and the interferometer OPD (Figure 4, right plot) although the dominant astigmatism portion remains the same. One possible explanation for this difference is that the interferometer measurement contains the double pass measurement of SHC optics and suffers more air turbulence induced wavefront errors.

4. SUMMARY AND FUTURE WORK

The AWCT provides a versatile facility for developing the wavefront sensing and control techniques and algorithms. The testbed has a good baseline optical quality and it is very easy to operate. After having finished the integration and alignment of the testbed the AWCT has entered into the WFSC test phase. Besides our testbed characterization and calibration, we plan to use this testbed to carry various wavefront sensing and control experiments. Following is a list of our currently planned WFSC tests and some initial ideas we want to try on this testbed in the near future:

- Sparse aperture wavefront sensing and control: besides the full circular aperture system the AWCT currently has we can change the pupil geometry to explore the wavefront sensing on a non-circular aperture or a sparse aperture.
- Multi-wavelength high dynamic range phase retrieval using the PRC: by measuring the wavefront at two or more different wavelengths the PRC can increase its dynamic range significantly. Our modeling and simulations have shown this could be a very powerful tool for measuring large wavefront aberrations and wavefront pistons from the segmented mirrors.
- Phase (instead of just focus) diversity for the PRC: using a calibrated wavefront phase corrector such as a deformable mirror we can add a known high order wavefront error to create high order phase diversity for the PRC.
- Amplitude retrieval on the PRC: using the PRC to not only to retrieve the wavefront phase error but also recover the wavefront amplitude.
- Extended-scene piston detection on the SHC: using the lenslets which are straddling across the segment mirror gaps with the extended scene to sense the absolute or relative wavefront piston from the segments.
- Explore the alternative and the optimal lenslet geometries for the SHC: study the tradeoff between the pupil spatial sampling and image content resolution for the extended scene SHC algorithm.
- Explore the open-loop control of using a DM: using the PRC to calibrate and verify the DM open loop control performance.
- Adaptive filter-based calibration approach for driving a DM
- Advanced image processing using knowledge of the system and adaptive optics: combining the wavefront knowledge with the imaging process.

With the powerful capability of the AWCT and more results coming out it we are sure there will be more ideas generated. It is our goal to accommodate various ideas to enrich the WFSC technique and algorithms. The testbed is and will be continuously evolving to suit the needs of WFSC development. It is our intention to use this testbed to create more collaboration with other institutes both inside and outside JPL and NASA.

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