Calibrating the Keck Pyramid WFS

Last updated: 23 June 2020

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Table of Contents

1 Instruments/ components

PyWFS: Pyramid wavefront sensor.
SAPHIRA: The infrared camera used as the detector for the PyWFS.
KPIC: Keck Planet Imager and Characterizer (of which the PyWFS is a part).
FIU: Fiber Injection Unit, a sub-system of KPIC.
CRED2: FIU infrared tracking camera.
NIRC2: Keck II facility near infrared imager.
PRTC: The PyWFS Real Time Controller.
DM: Keck II deformable mirror.
DTT: Keck II tip-tilt mirror (Downstream Tip Tilt).
WC: Wavefront controller.

2 GUI descriptions

2.1 Calibration menu

The calibration menu gives access to the different calibration processes, as well as additional tools for assessing the system.

Figure 1: PyWFS calibration menu

- **Calibration setup**. Launches the calibration setup procedure. This sets the PyWFS optics and configures the PyWFS.
- **Closed loop check.** Opens the loop control GUI and configures the PyWFS for the selected instrument.
- **Image sharpening.** Opens the image sharpening dialogue. This is used to run the standard image sharpening tool for NIRC2 and record the reference signals for the PyWFS.
- **PyWFS registration.** Runs the PyWFS registration process. This process is also carried out during the calibration setup.
- **Interaction matrix.** Launches the Interaction Matrix tool, for recalibration of the PyWFS.
- **PyWFS pick-off.** (**2.5.1 PYWFS PICK-OFF**).
- **Configure PyWFS**. (**2.5.2 CONFIGURE PYWFS**).
- **Modulator control.** (**2.5.3 MODULATOR CONTROL**).
- **Tip-tilt control.** (**2.5.4 TIP-TILT CONTROL**).
- **DM Zernike control.** (**2.5.5 DM ZERNIKE CONTROL**).
- **Loop display.** (**2.2 PYWFS LOOP DISPLAY**).
- **AO control.** (**2.3 PYWFS LOOP CONTROL**).
- **PyWFS status.** (**2.4 PYWFS STATUS**).
- **Shutdown.** Shuts down the PyWFS. Should be executed after the calibrations are complete. Removes the PyWFS pick-off optic from the path of NIRC2 and shuts down the PyWFS camera.

2.2 PyWFS loop display

The PyWFS loop display shows the real time status of the PyWFS and AO loops. The PyWFS image is displayed, showing the 4 images of the telescope/bench pupil that are created by the PyWFS. Figure 2 shows an example of this display during afternoon calibrations for NIRC2.

Information about the quality of the correction (as measured by the PyWFS) is also displayed, including the wavefront error and tip-tilt residuals.
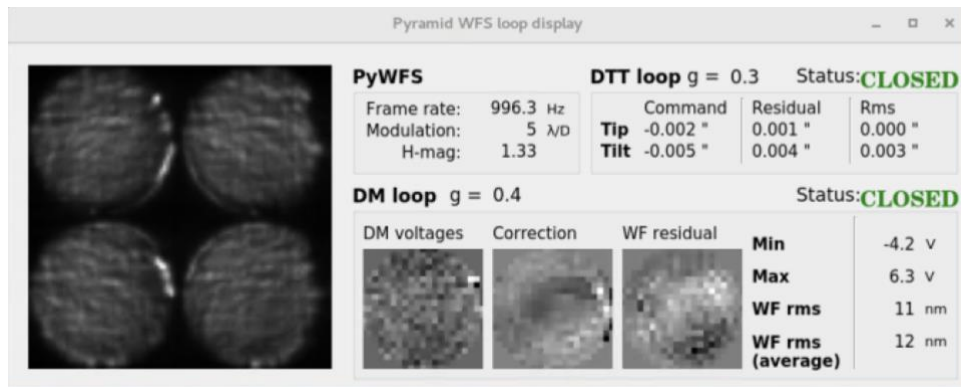

Figure 2: PyWFS loop display

2.3 PyWFS loop control

The PyWFS loop control GUI allows the user to open and close the loops, set the loop gains and set the modulation. The display shows an intensity map of the illuminated pixels. This is a sum of the four pupil images averaged over 1 second.
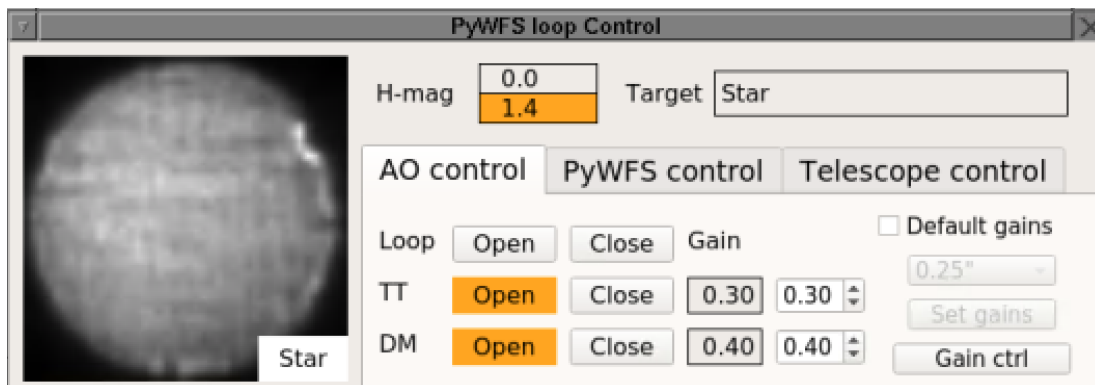

Figure 3: PyWFS loop control
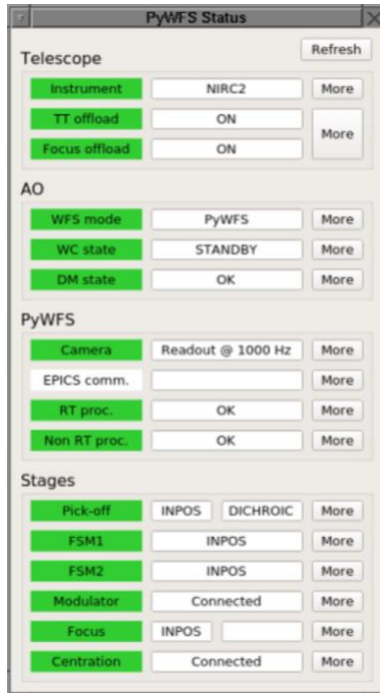
2.4 PyWFS status

Figure 4: PyWFS status GUI

The status GUI displays the current state of various sub-components and processes of the PyWFS and should be the first place to look in the case of any errors.

The subsystem labels are colored accordingly:
- Green: OK.
- Yellow: moving/setting up.
- Red: Error.

2.5 Tools

Additional tools and GUIs can be accessed from the calibration menu.

2.5.1 PyWFS pick-off
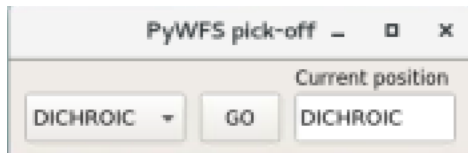

Figure 5: PyWFS pick-off GUI

The PyWFS pick-off GUI allows individual control of the current PyWFS pick-off optic in front of NIRC2. The user can select the desired pick-off optic:
- DICHROIC: for PyWFS operation with NIRC2.
- MIRROR: for PyWFS operation with the FIU/NIRSPEC.

Alternatively, the pick-off can be set to OPEN when the PyWFS is not in use (clears the path to NIRC2).
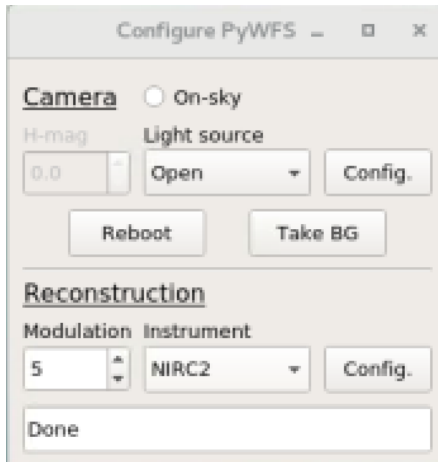
2.5.2 Configure PyWFS

Figure 6: PyWFS configuration GUI

The PyWFS configuration GUI allows for:

1. Configuration of the PyWFS camera for a given magnitude or light source. A background measurement can be taken (the light should be blocked by the user) and the camera can be rebooted.
2. Configuration of the wavefront reconstruction for a given instrument and modulation. This loads the appropriate reference signals for the instrument and the appropriate interaction matrix for the modulation.

These processes are done automatically during the calibration steps (i.e. in the closed loop check depending on the instrument selected).

2.5.3 Modulator control
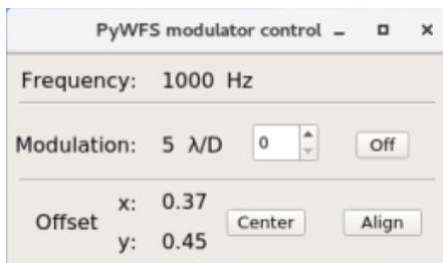
Figure 7: PyWFS modulator control

The modulator control GUI allows:

- Monitoring of the modulation parameters.
- Setting the modulation amplitude or switching the modulation off.
- Positioning of the modulator at its center (0.5,0.5).
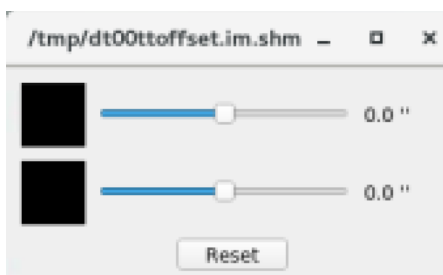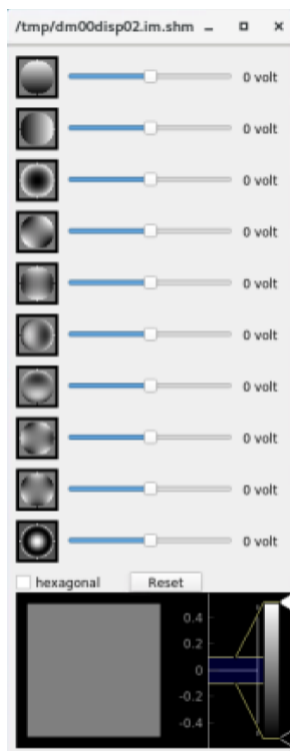- Alignment with the PyWFS.

2.5.4 Tip-tilt control

Figure 8: Tip-tilt control

The tip-tilt controller allows open loop control of the tip-tilt mirror (DTT). This is useful for checking the response of the system.

2.5.5 DM Zernike control

Figure 9: DM Zernike control GUI

The DM Zernike control GUI allows open loop control of the first 10 Zernike modes. This is useful for checking the response of the system, particularly to see if the DM is responding in PyWFS mode (i.e. is the PyWFS connected to the DM).

3 Afternoon calibrations

Afternoon calibrations should be carried out before each night on-sky. These include registration of the DM with respect to the PyWFS pixels, image sharpening, minimization of any focus error, and measurement of reference slopes (equivalent to the Shack-Hartmann COG measurement).

Note: The PyWFS calibrations can be done for different science instruments: NIRC2, FIU or the CRED2 (KPIC focal plane camera). However, as of 2020 the FIU and CRED2 are not facility instruments and so the image sharpening for these instruments is not fully automated. See section **3.2 NOTES ON CALIBRATIONS FOR THE FIU AND CRED2**.

3.1 Procedure
Session: k2obsao

1. Setup Keck II AO bench
Run the standard Keck II AO calibration setup. This will setup the AO bench but not the optics specific to the pyramid WFS.

    a. Open the `Calibration tools` menu from the background menu:

        `K2 AO Tools` > `Calibration Tools`.

    b. From the calibration menu select `Calibration setup`.

    c. When prompted select `NIRC2` as the instrument and `NGS-AO`.

    d. Complete the `Calibration setup` and dismiss.

    e. Check that the **internal light source is switched ON** and **switch the HEPA filter OFF**:

        `Calibration Tools` > `Light Source Control`.

2. Start PyWFS calibrations
Start calibrations for the pyramid WFS:

    a. Launch the PyWFS calibration tools from the background menu:

        i. `K2 AO Tools` > `PWS OPS` > `Calibrations`.

    b. Confirm the following windows are open (**FIGURE 10**):

- `PyWFS calib` menu (**2.1 CALIBRATION MENU**).
- `PyWFS status` display (**2.4 PYWFS STATUS**).
- `PyWFS loop display` (**2.2 PYWFS LOOP DISPLAY**).
- `prtcStartCalibrations` terminal.

    c. The image in the `PyWFS loop display` will differ (see **FIGURE 12**) depending on the initial state of the PyWFS (i.e. if the PyWFS camera is running at the start of the calibrations).
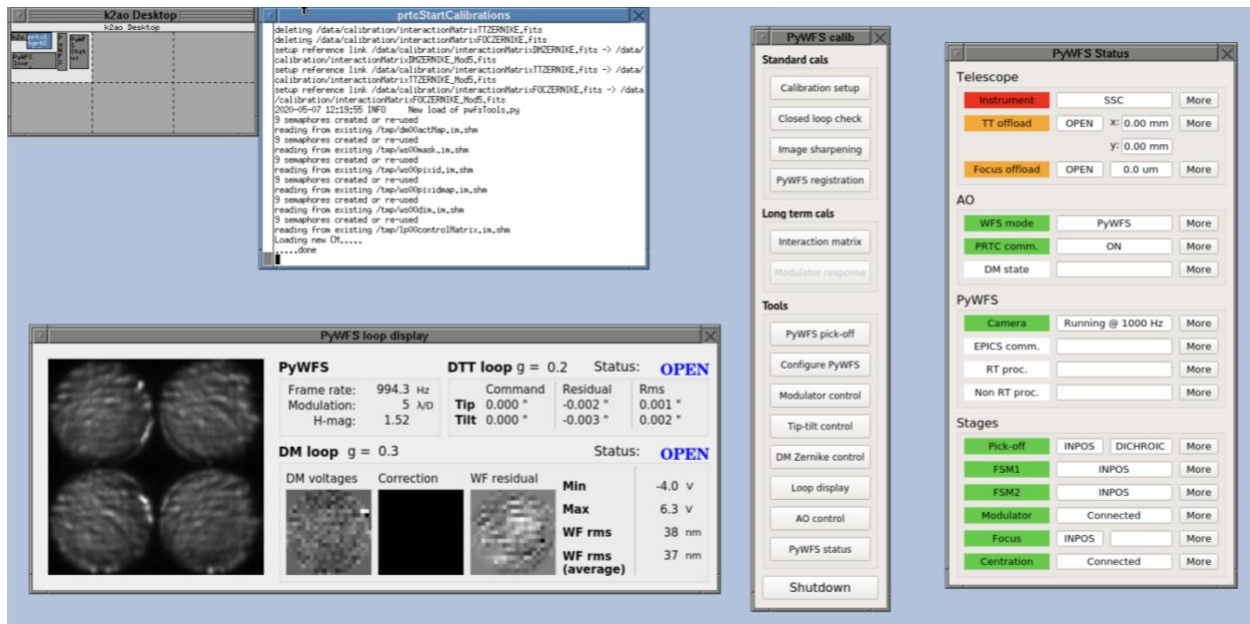
Figure 10: GUIs and terminal for running PyWFS calibrations.

3. Calibration setup

The `Calibration setup` will set the positions of the PyWFS optics, initialize the PyWFS camera and connect the PyWFS to the AO system. Finally, it will begin the reconstruction process and set the default parameters.

The progress of each step will be displayed in the status window next to the buttons, with further details in the terminal window. The status window will display `Done` after the process is complete, or an error message if the process fails.

You can monitor the `PyWFS loop display` to check the image on the PyWFS camera. **FIGURE 12** shows examples of what to expect at different stages of the setup.

a. Click the `Calibration setup` button in the `PyWFS calib` menu. This will open the `PyWFS calibration setup` GUI (**FIGURE 11**).
b. Select the appropriate optic, depending on the science instrument:
   - `DICHROIC`: for NIRC2. No light to the FIU/NIRSPEC.
   - `MIRROR`: for the CRED2 or FIU. No light to NIRC2.
c. Click the `Optics setup` button. This will:
   - Set the selected pick-off optic.
   - Set the PyWFS focus to the last calibrated position for the selected optic.
   - Set the SFP to the `pws` position.

d. Click the `Init PyWFS camera` button.
- The internal white light source is blocked (for background measurements).
- The SAPHIRA is setup for the brightest light setting (`open`), equivalent to an H-band magnitude of ~1.5. The PyWFS calibrations are done using this bright light setting.
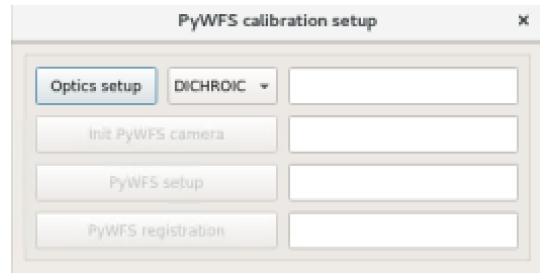- A background measurement is taken.

Figure 11: PyWFS calibration setup

e. Click the `PyWFS setup` button.
- The process will check that the light is on. The light is switched on during the standard Keck II AO calibration setup (**1. SETUP KECK II AO BENCH**).
- The light will be set to `open`.
- You can check there is light on the PyWFS camera (in the `PyWFS loop display`). The image should look something like **FIGURE 12C**.
- The PRTC will be connected to the AO system, allowing for the AO correctors (the DTT and DM) to be controlled by the PyWFS.
- The modulator is set to the default value of 5 λ/D.
- The modulator is aligned with the PyWFS. An error is produced if the modulator saturates.
- The reconstruction process is started and the PyWFS reconstructor is configured.
- The DM is set to the pyramid flat state and any tip-tilt offsets are removed.
f. Check the PyWFS image in the `PyWFS loop display`. The light should be aligned with the PyWFS, showing four equally illuminated quadrants (**FIGURE 12F**).
g. Click the `PyWFS registration` button.
- The 4 PyWFS pupil images on the detector are identified and their locations are updated in the PRTC for the processing of the WFS signals.
- A popup appear displaying the shift of the pupil from the previous location. This should typically be <= 2 pixels. If the shift is >4 pixels this suggests some change on the AO bench: a message will appear suggesting a recalibration of the system (IM measurement).
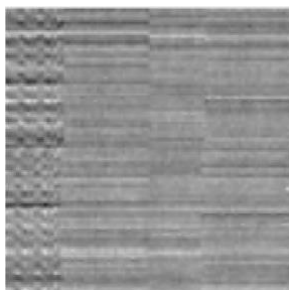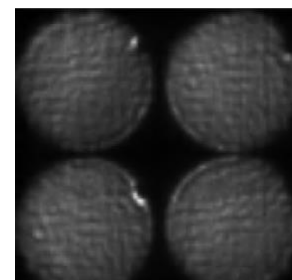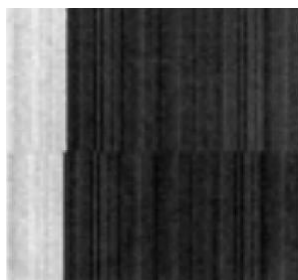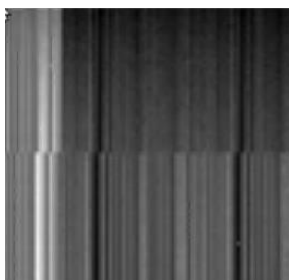

a) Image with background removed, no light.
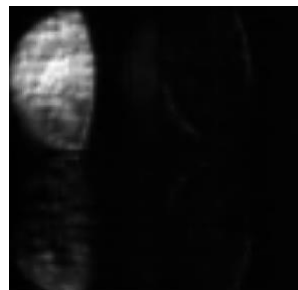
b) Image during insertion of pick-off optic.
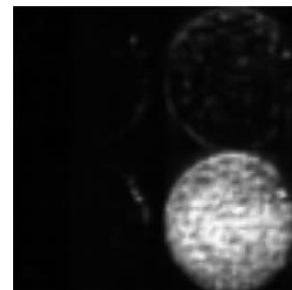
c) Image before alignment.

4. Closed loop check

The `Closed loop check` opens the loop control GUI and is used to check the closed loop performance. First you will be asked to select an instrument: this will set the reference slopes, light level and camera configuration suitable for this instrument. The user should then set the gains and check the TT and DM loops are well behaved.

a. Click the `Closed loop check` button.
   - Select `PyWFS only` from the prompt or, if you wish to go straight to the instrument check out and skip the image sharpening, select the desired instrument (see **6. IMAGE CHECKOUT: NIRC2**).
   - The `PyWFS loop control` GUI is opened.
b. Set the loop gains:
   - Check the `Default gains` checkbox in the loop control GUI.
   - From the dropdown menu select `High` default gains.
   - Click `Set` to apply the gains.
c. Monitor the loop in the `PyWFS loop display` window.
d. Close the loops from the `PyWFS loop control` GUI.
e. Assess the loops:
   - Check the stability: are any actuators/modes noticeably oscillating. If yes open the loops immediately. There are two possible solutions to these instabilities:
     - o Re-run the registration from the dedicated button `PyWFS registration`.
     - o Re-calibrate the interaction matrix.
     If the loops are stable continue with the assessment.
     i.   Are the DM voltages within the +/-10V range?
     ii. Is the tip-tilt residual smaller than 0.005"?
     iii. Is the average residual WF less than 30nm rms?
   - If the answers to i – iii are all yes, proceed with the calibrations. Otherwise a re-calibration of the system may be required.
f. Open the loops and close the loop control GUI.

5. Image sharpening

After the setup and closed loop check the system is calibrated for the science instrument. This includes image sharpening (or equivalent), focus minimization and measurement of reference slopes (similar to the Shack-Hartmann COG measurement). The PyWFS calibrations currently have completely automated tools only for NIRC2. These are based on the standard NIRC2 image sharpening tools. The NIRC2 process is described here, please see **3.2 NOTES ON CALIBRATIONS FOR THE FIU AND CRED2** for other instruments.

a. Click the `Image sharpening` button.
   - The `Image sharpening menu` is opened (**FIGURE 13**).
b. Select the instrument for calibration: `NIRC2`, the `CRED2` or the `FIU`.
c. You can choose to skip the image sharpening and use the current DM map.
d. Click the `Image sharpening` button (in the `Image sharpening menu`).

Figure 13: Image sharpening menu

   - The light is blocked for initial background images with the science instrument.
   - The PRTC is disconnected from Keck II AO to avoid communication confusion and the MGAOS is set to `Normal`.
   - The standard NIRC2 image sharpening tool is called, with some adjustments for the PyWFS.
e. Confirm the NIRC2 image sharpening GUI and terminal are opened (see **FIGURE 14**):
   - The standard `Image Sharpening Tool` will appear.
   - The terminal is behind the GUI, it may be useful to monitor the progress of the image sharpening code here.
f. Select `Auto image sharpen` from the `Image Sharpening Tool`.
   - 3 iterations of image sharpening will be run, with the SFP focus adjusted for different out of focus images.
   - At the end the new DM map will be saved to the K2 DM voltages folder and the focus (z) position of the SFP will be updated for the `pws` position.
   - This process takes ~15 minutes.
g. After the image sharpening is complete, in order to move onto the next step **you MUST CLOSE all the image sharpening windows**: the `Image Sharpening Tool`, the terminal window and the display of the DM voltages (all windows in **FIGURE 14**).
   - The voltages are then automatically saved to the PRTC as the default DM map.
   - If you don't close all the windows the `Image sharpening menu` will not enable the next button.
h. Click the `Tune PyWFS focus` button.
   - The focus is minimized over several iterations using the PyWFS signal and adjusting the position of the PyWFS focus stage.
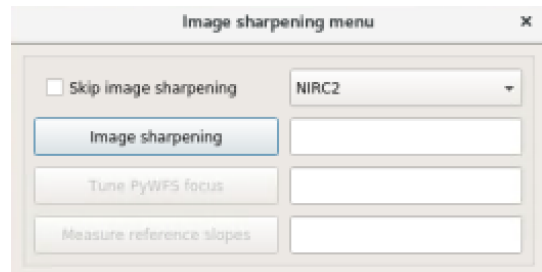
- The focus is saved to the named position associated with the current pick-off optic (`DICHROIC` for NIRC2).
i. Click the `Measure reference slopes` button.
   - A modulation of 2 λ/D is set.
   - The TT loop is closed.
   - The reference slopes are recorded and saved for the given instrument and configuration (modulation and pick-off optic).
   - The process is repeated for modulations 3, 4, and 5 λ/D.
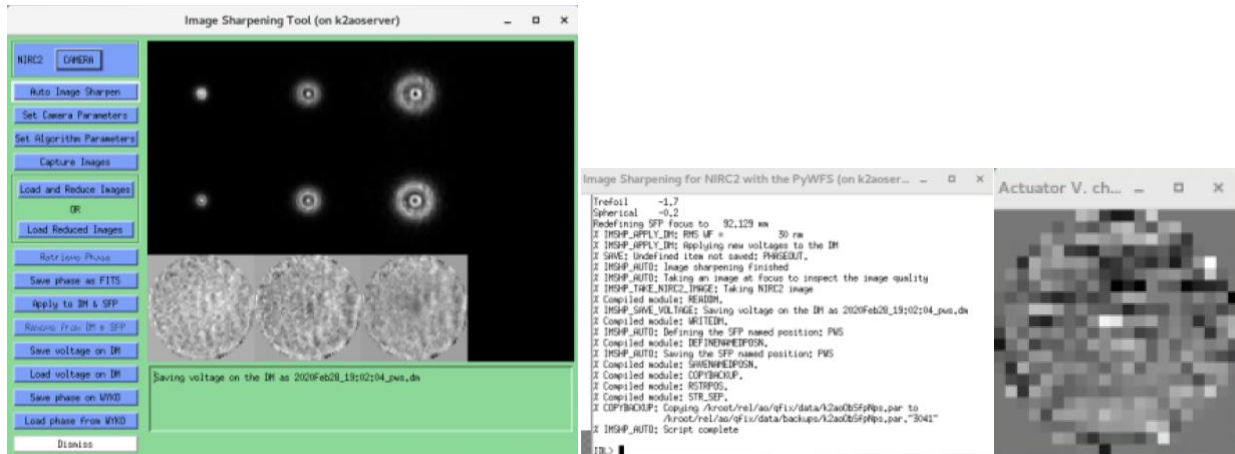

Figure 14: Screenshots of the image sharpening graphics. From left to right: the image sharpening tool; terminal window and output voltage map. All should be dismissed after completion to continue the PyWFS calibration process

6. Image checkout: NIRC2

After the image sharpening has been complete, checkout the image quality on NIRC2 in open and closed loop.
   a. Click the `Closed loop check` button.
      - Select `NIRC2` when prompted to select the instrument.
      - The appropriate PyWFS parameters will be set and the light set to filter `ND2`.
      - The `PyWFS loop control` GUI is opened.
   b. Set the loop gains:
      - Check the `Default gains` checkbox in the loop control GUI.
      - From the dropdown menu select `Low` default gains.
      - Click `Set` to apply the gains.
   c. Open the NIRC2 operating software.
   d. Take an image using the `br_gamma` filter with the loops open and with the parameters adjusted for the light filter `ND2`. Adjust the integration time to avoid saturation. Suggested parameters:
      - `subc = 512`
      - `tint = 0.05`
      - `coadds = 25`

e. Then close the loops on the PyWFS using the `PyWFS loop control` GUI and take additional images on NIRC2:
   a. Check quality of the NIRC2 image (see **FIGURE 15**). The FWHM of the images should be ~4.3 pixels.
   b. Monitor the closed loop in case of instabilities.
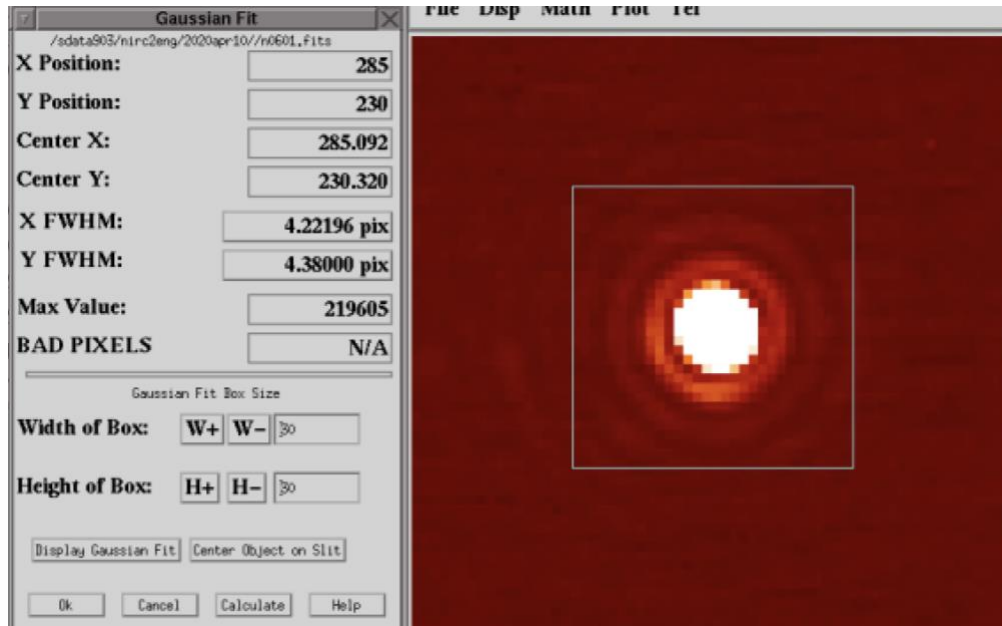f. Open the loops and close the `PyWFS loop control` GUI.

Figure 15: Example NIRC2 image and Gaussian fit

7. Shutdown

After the calibrations are complete the system should be shutdown, using the `Shutdown` button at the bottom of the calibration menu.

a. Click the `Shutdown` button.
b. You will be prompted to confirm if you want to continue with the shutdown: click `OK`.
c. The Shutdown process will:
   • Open the loops.
   • Stop communication between the PyWFS and Keck AO.
   • Stop the modulator.
   • Remove the pick-off optic.
   • Stop the PyWFS camera.
d. At the end of the process a message will appear (**FIGURE 16**) informing you of any errors in the shutdown process and warning you to turn off the calibration source (this will not be done automatically). The shutdown process can take a couple of minutes to complete to ensure the pick-off optic is fully removed.
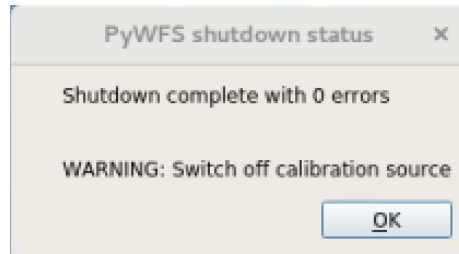
Figure 16: Message sent after shutdown is complete, with warning to switch off the calibration source

3.2 Notes on calibrations for the FIU and CRED2

The FIU and CRED2 are not facility instruments, and as such they do not have fully automated calibration scripts yet. However, with input from the KPIC team the above procedure can be used to setup the calibrations for the FIU or CRED2 with the following adjustments:

1. Image sharpening for the chosen instrument should be carried out (typically by Sam Ragland or Jacques-Robert Delorme). The result should be a DM voltage map saved either in KROOT or on the PRTC. Check the following:
   a. Where are the voltages saved?
   b. What is the name of the file?
   c. Should the PyWFS calibration files be saved using FIU or CRED2 as the selected instrument?
2. In step **3. CALIBRATION SETUP** select the `MIRROR` as the pickoff optic. During the setup the sfp will be set to the `CRED2` position (if the `MIRROR` is selected) rather than the `pws` position (used with the `DICHROIC`).

N.B. the CRED2 can be calibrated with the MIRROR or DICHROIC in the path – the calibration files include the name of the pickoff optic in place at the time. However, the PyWFS AO Acq. GUI will currently automatically setup the bench with the MIRROR in the path for the CRED2. To use the CRED2 with the DICHROIC you must separately adjust the pickoff optic to DICHORIC after the PyWFS Start of night script.

3. In step **5. IMAGE SHARPENING** select `FIU` or `CRED2`. Click on the `Image sharpening` button and a popup will appear asking the user if they want to load the DM voltages from KROOT or the PRTC (left, **FIGURE 17**). Select the appropriate option depending on where the voltages were saved.
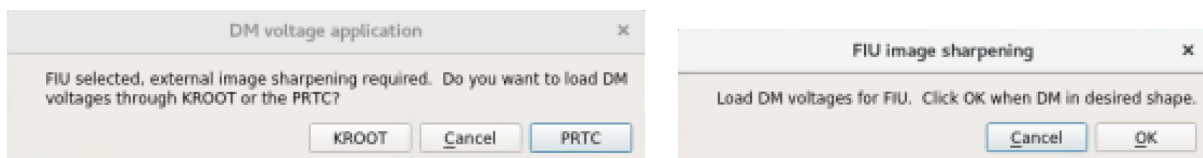

Figure 17: Popup prompts for image sharpening for the FIU.

4. A second popup will appear prompting the user to now load the voltages. For example, if the voltages are stored on KROOT:

<div align="center">

`K2 AO Tools` > `Calibration Tools`
> `DM control` > `Load DM voltages`

</div>

Then select the appropriate file (see **FIGURE 18**). Only when the voltages are loaded should you click OK in the image sharpening popup (right, **FIGURE 17**).
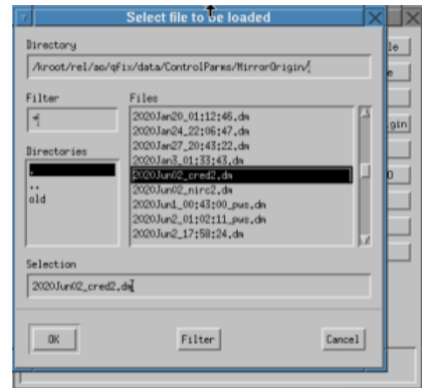
After loading the DM voltages proceed with the `Tune PyWFS focus` and `Measure reference slopes` steps.

Figure 18: Example of loading an FIU/CRED2 voltage map from KROOT

In the future automated image sharpening processes for the FIU and CRED2 can be connected to the image sharpening button in the same way that the NIRC2 image sharpening is done.

4 Long term calibrations

4.1 'pws' SFP position

Every so often the pws SFP position should be checked, in terms of the x/y location on NIRC2. The PyWFS was originally aligned with the L-band vortex coronagraph, this is now roughly the center of NIRC2, at the pixel location (for NIRC2s full frame, narrow camera): (540,498).

4.2 Interaction Matrix

The interaction matrix button will be highlighted if it has been more than 60 days since the last calibration for modulations 3 – 5. At this point you should recalibrate the system. You should also consider recalibrating if the AO bench has been accessed or if the pupil images have shifted by a large amount (>4 pixels).
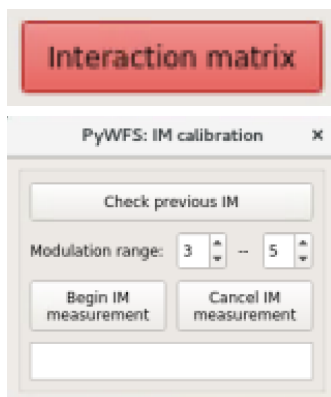
Figure 19: Interaction matrix button (top) and GUI (bottom).

5 Trouble shooting

5.1 Status errors

- The `PyWFS Status` GUI monitors the communication and settings of different parts of the AO system and PyWFS, and should be the first place you look during troubleshooting.
- An error is indicated when an individual process is highlighted red.
- Further information and access to recovery procedures can be accessed through the `More` buttons.
- If the PyWFS camera has faulted, restart this first: the frame rate is the trigger for various processes.
- The second priority error is the EPICs communication: restart this to ensure the status GUI correctly reflects the current state of the instrument.
- After executing any recovery procedure check that the error no longer appears in the status GUI: if the error persists more in-depth trouble shooting may be required.
- The status GUI includes a refresh button at the top. This will execute all the callback functions and should be used to confirm the information shown in the status GUI is up-to-date.

Telescope
During calibration/ bench operation we can ignore any telescope errors.
- **Instrument**
  For PyWFS operation the telescope must be configured for `NIRC2`.
- **TT/ focus offload**
  The status should be yellow (offload off) or green (offload on). If state in the EPICS channel is anything else the status will be red (unknown). The `More` button will open the detailed offloading GUI.

AO
- **WFS mode**
  The status will be green if the AO software is configured for `PyWFS`, otherwise it will be red. The procedure for switching the software between `PyWFS` and `SHWFS` is found on the Twiki: https://www.keck.hawaii.edu/twiki/bin/view/Main/PyWfsOpsRevert.
- **WC state**
  For PyWFS operation the Shack-Hartmann wavefront controller (WC)/MGAOS must be in `STANDBY` (if it is in `NORMAL` it is possible for both the Shack-Hartmann and PyWFS to send commands to the DM at the same time). The `More` button will open a GUI (see **FIGURE 20**) which allows the user to set the WC to `NORMAL` or `STANDBY`.
- **DM state**
  The status will be red if the DM commands contain nans, yellow if they are all zeros and green otherwise. The `More` button will open the `DM recovery` GUI (see **FIGURE 20**) for use to reset the DM in the PRTC channels when they contain nans.
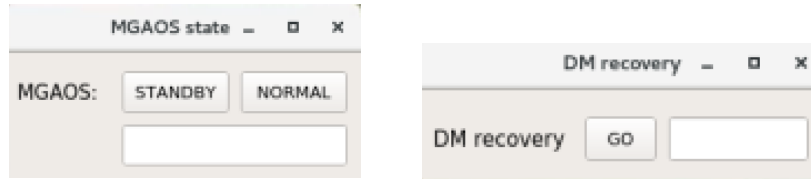
Figure 20: Recovery procedure GUIs for AO processes.

PyWFS

- **Camera**
  The status will be green if the camera is running, yellow if it is in the process of setting up and red if the camera has been shut down or if the frame is corrupted. The `More` button opens the `SAPHIRA state` GUI (see **FIGURE 21**) which:
    - Shows the key SAPHIRA camera parameters.
    - Can display the live camera frame at different processing stages: see **FIGURE 22**.
    - Can reboot the SAPHIRA camera (if camera is off/in case of a corrupted frame).
- **EPICs communication**
  If EPICs communication with the PRTC fails the status will be red. To restart the communication, click the `More` button and use the `PyWFS EPICs comm.` GUI (**FIGURE 21**).
- **RT processes**
  If any of the real time (RT) processes fail this status will be red. To restart use the `RT processes` GUI (**FIGURE 21**), accessed through the `More` button.
- **Non-RT processes**
  If any of the non-RT processes fail this status will be red. To restart use the `Non-RT processes` GUI (**FIGURE 21**), accessed through the `More` button.
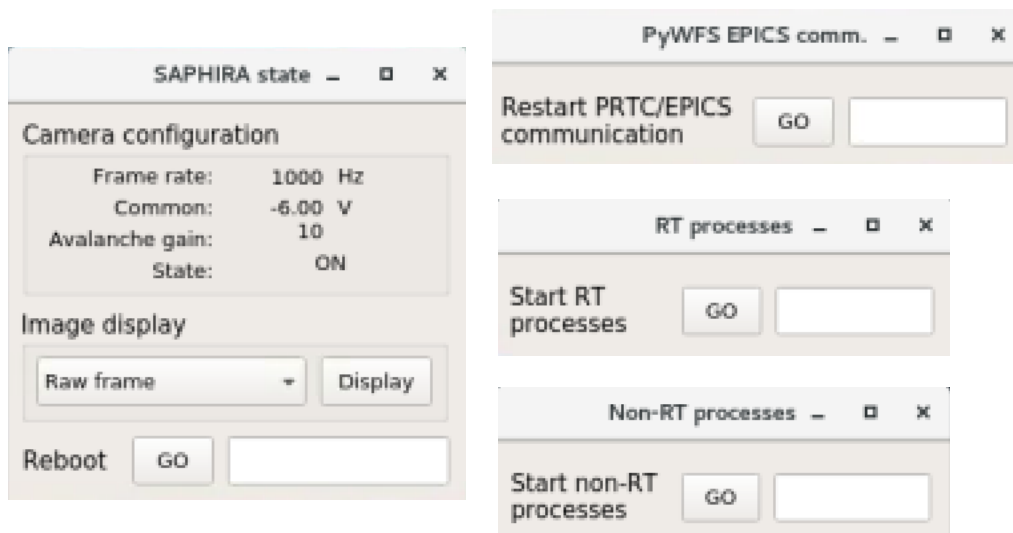

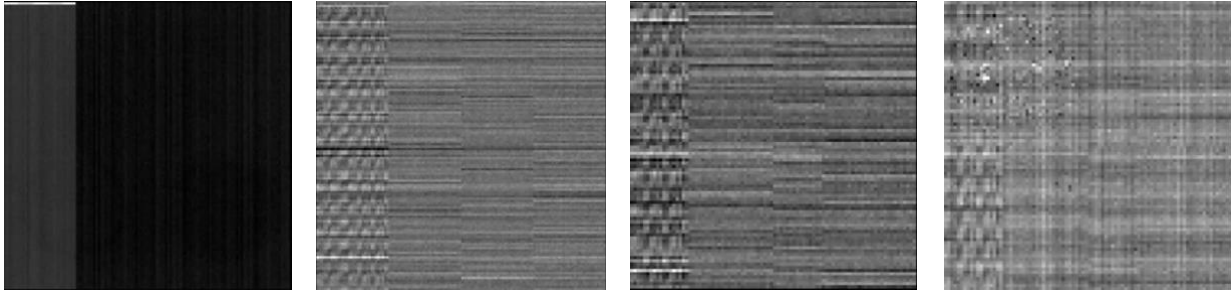
Figure 21: GUIs for PyWFS processes.

Figure 22: Examples of SAPHIRA frames at different processing stages. From left to right: 1) raw full frame. 2) full frame: background and flat field applied. 3) small frame: cropped to pupil image area with background and flat field applied. 4) average of 1000 small frames. Frames shown with no light and configured for an H-mag of 1.5.

Stages

The current state of each of the PyWFS stages is shown, highlighted red if there is a fault, yellow if the stage is moving and green if it is in position. For each stage the `More` button opens a dedicated GUI for that stage, allowing bypassing of faults and direct access to the positioning of the stage.

5.2 Calibration errors

Light is OFF

- Turn on the white light source:
    `Calibration Tools` > `Light Source Control.`

SFP faulted

- Check the SFP using the SC GUI and jog/re-initialize if necessary.

No PyWFS image (during alignment)

- Reset the EPICs communication with the PRTC:
    `PyWFS Status GUI` > `EPICS comm.` - `More` > `Restart PRTC/EPICS communication` - `GO`

Pupil location

- Invalid pupil locations:
    1. Check PyWFS image: is there light on the PyWFS? Is the modulator running and aligned with the PyWFS? Is the image updating?
    2. After correcting any issues with the alignment or PyWFS image re-run the registration.
- Large shift (>4 pixels):

1. Double check the registration (`PyWFS registration` button on `Calibration menu`).
2. If the shift remains it means something has shifted in the system: think about recalibrating the system (i.e. the interaction matrix).

5.3 Performance issues

Instabilities during closed loop

- Check:
    1. Is the modulation is running.
    2. Is the HEPA off?
    3. Is the correct IM loaded?
    4. Are the real-time and non-real time processes running?
    5. Are the pupils correctly identified? Try re-running `PyWFS registration`.
    6. Try the `PyWFS only` option to see if instabilities only occur with a particular instrument (i.e. particular reference slopes):
        a. If the loop is still unstable may need to re-calibrate (`Interaction Matrix`).
        b. If the loop is stable try recalibrating the reference slopes for the unstable instrument option (`Image sharpening`).