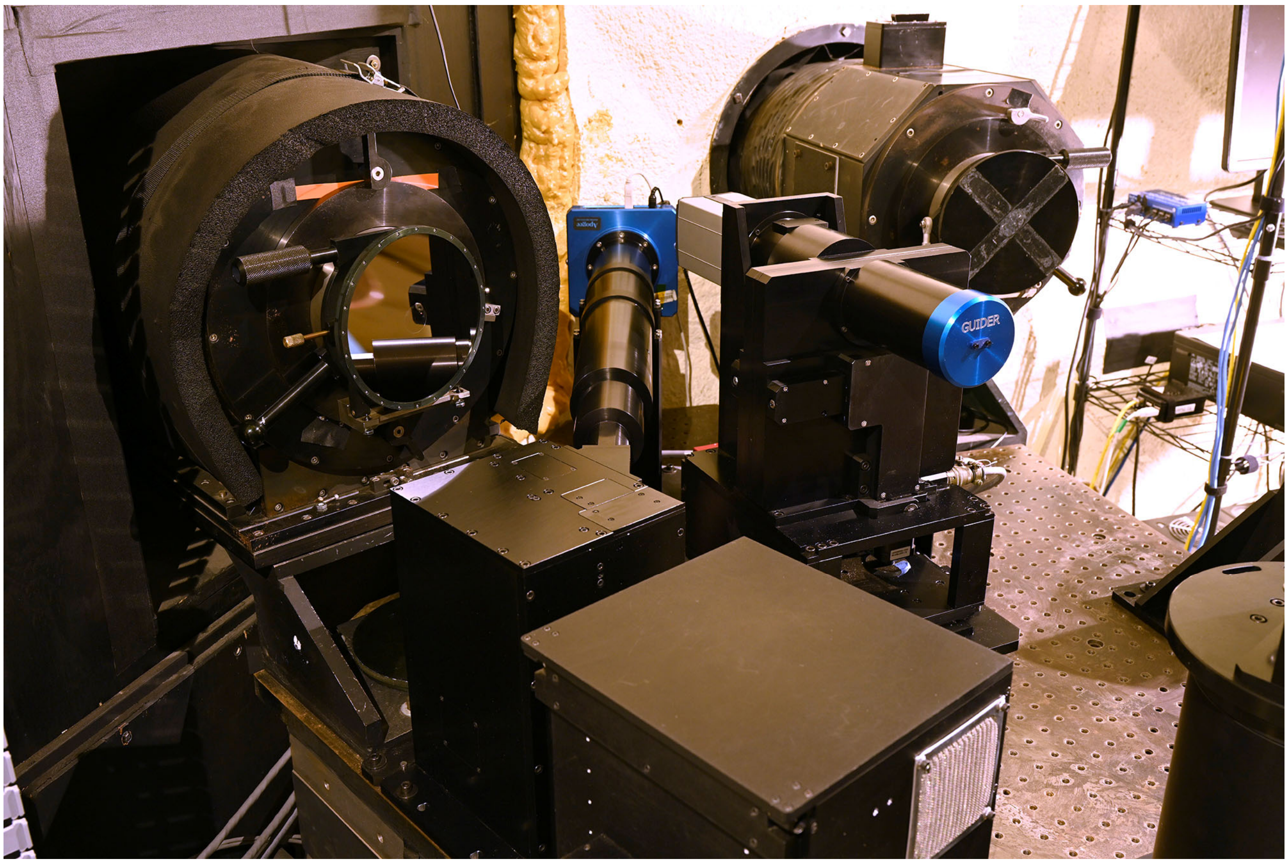
User manual for the HJST coude wavefront sensor



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1 Introduction

The HJST (Harlan J. Smith Telescope) changes coude focus due to factors including the telescope temperature, where the telescope is pointing in the sky, and whether or not the iodine cell is inserted. To allow easy, quick, and precise focusing of the HJST on the slit of TS2 (Tull Spectrograph 2 / 2dcoude), a wavefront sensor has been installed and commissioned as part of the TS2 preslit hardware. The WFS is software controlled, operated by the observer, and is the recommended way to focus the telescope. All previous methods of focus remain fully functional. The WFS was installed in March 2020, and commissioned in October 2020.

Please see **section 3** for a recipe-style **Quick Start Guide** on pages 9 - 11.

2 Basic operating principle

The wavefront coming in from a distant star is a planar surface. After passing through the Earth's atmosphere and a telescope's optics, the wavefront has typically become aberrated and is no longer planar. Any position on the aberrated wavefront will have some amplitude and gradient deviation from a flat surface. As its name suggests, wavefront sensing measures the shape of the wavefront. The TS2 wavefront sensor uses a Shack-Hartmann optical design for this purpose. The telescope focuses a star at or near the center of the WFS entrance aperture that has an 11 arcsecond diameter, and the WFS Fabry lens then collimates that light *and* produces an image of the telescope primary mirror on a lenslet array (flies eye like array of 0.5 mm square lenses). Each lenslet forms an image on a unique part of the WFS detector with the light from a unique 15 cm square area of the telescope primary mirror, and each of those images is of the WFS entrance aperture (the star in the 11 arcsecond field of view of the aperture). Figure 2 is an example of a TS2 WFS image of a star, and figure 3 is a TS2 WFS image with the telescope pointing at the flat field screen. The information in the Shack Hartmann WFS image is the position of each spot, which is a measure of the gradient of the wavefront at the spot's location in the wavefront. The lenslets sample the gradient on a square grid that maps to a 15 cm square grid across the 2.72 m primary mirror.

The wavefront sensor system also includes an internal artificial reference star. Software reduces the images of the reference star and actual star to determine the shape of the wavefront. The wavefront typically has a complicated shape, and that shape is expressed as the sum of the family of Zernike polynomials, with the amplitudes of each polynomial being the set of variables for the fit. Each individual polynomial is a surface, and is orthogonal to all other Zernike polynomials. Again, an amplitude coefficient for each polynomial is the output of the WFS data reduction, and only the first 39 Zernikes are fitted (higher Zernike coefficients are set to zero). Zernike polynomials are used because each polynomial maps onto a particular optical aberration such as 3^{rd} order spherical aberration, 3^{rd} order X coma, 3^{rd} order Y coma, and for our immediate purposes, defocus.

A sketch of the optical components that feed the WFS is shown in figure 1. The WFS feed is seen before the TS2 slit, and after the iodine cell. The WFS feed has two probes, the reference star probe and the WFS pickoff probe, that can be independently inserted into, and retracted from the telescope light path. All four combinations of the two probes positions have a use, and are described below.

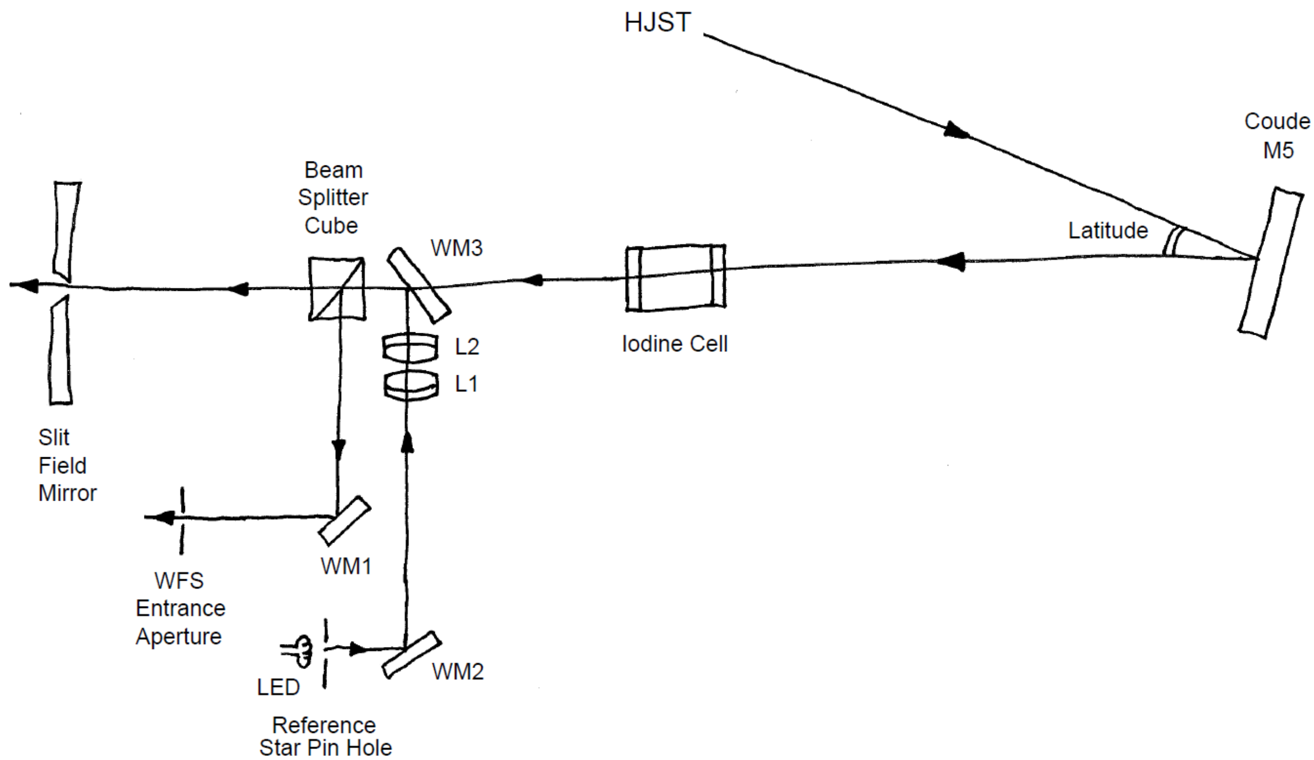


Figure 1: this sketch shows the optomechanical layout that feeds the 2dcoude wavefront sensor in the preslit system. The coude light from the telescope comes down from top-center of the figure to the Coude Mirror 5 at right, then travels horizontally to the slit in the field mirror at left. The iodine cell can be inserted and retracted from the light path (shown inserted). The WFS reference star, and the WFS pickoff can also be inserted and retracted from the light path (both shown inserted). Photographs are in a later section of this document.

Normal observing (mode 1): this mode has both probes retracted as shown in figure 4. The full guider acquisition field of view is unobstructed by the WFS system in this mode, so that normal target acquisition, guiding, and observing can take place.

Wavefront sensing (mode 2): the wavefront sensor pickoff is inserted into the telescope optical path as shown in figure 5. The pickoff uses a 90-10 beam splitter cube of 20 mm edge length. The cube reflects 90% of the light down to a folding mirror, which in turn reflects the light to the entrance aperture of the WFS. The entrance aperture is co-focal with the TS2 slit. The other 10% of the telescope light passes through the cube to the field mirror and slit so that the guider can autoguide during wavefront sensing. It is a mistake to take TS2 data in this mode due to the 10% transmission of the beam splitter cube. It should be noted well that when the star is in focus on the slit for normal observing, the star will be slightly out of focus on the guider in this mode due to the extra optical path length through the beam splitter cube. Do not use the guider in this mode for a detailed assessment of the image quality.

WFS calibration (mode 3): both probes are inserted as shown in figure 6. This allows a reference image to be taken by the WFS of the reference star. Information from this image is used in the WFS data reduction. A reference image can be taken at any time, but it is likely the image will stay valid from when it is taken until work is undertaken on the WFS that might change the WFS optical alignment. Taking and reducing the reference image is described in section 5, and is not usually an observer's task.

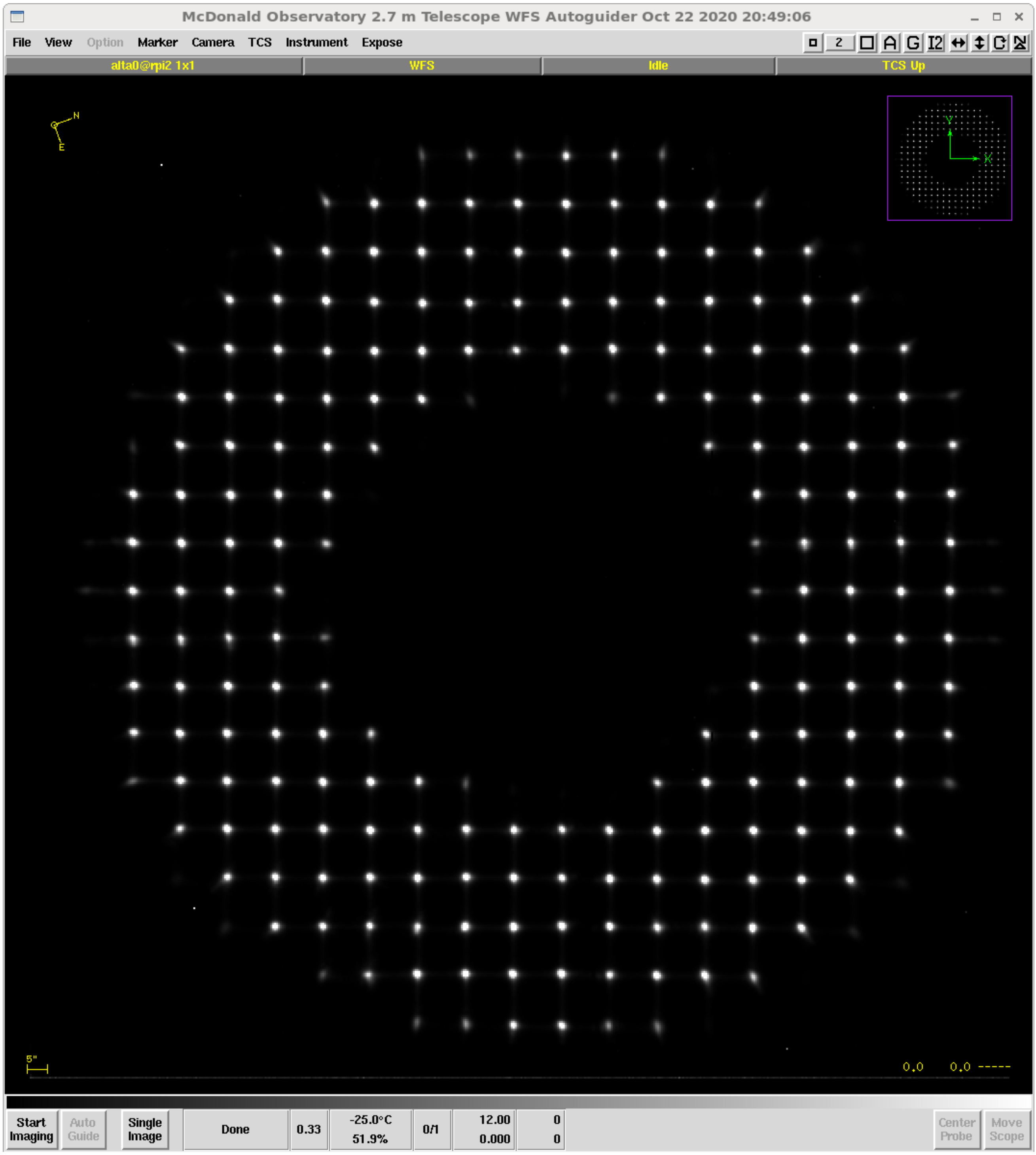


Figure 2: An early version of the main window of program ts2*wfs* shown displaying the wavefront sensor image of a star. The window format of the current software version is seen in figure 10. The software is based upon the tsgdr coude guider software, and shares most of the tsgdr functionality. The spot-to-spot separation is 11 arcseconds on the sky, and 25 pixels on the WFS detector. This image is from a time of very good seeing, hence small FWHM spots.

Reference star check (mode 4): only the reference star probe is inserted as shown in figure 7. This allows the observer to use the guider to check that the reference star is imaging on the center of the slit. There are no user adjustments, so this is a step that could be used during instrument setup as an indicator of the WFS health.

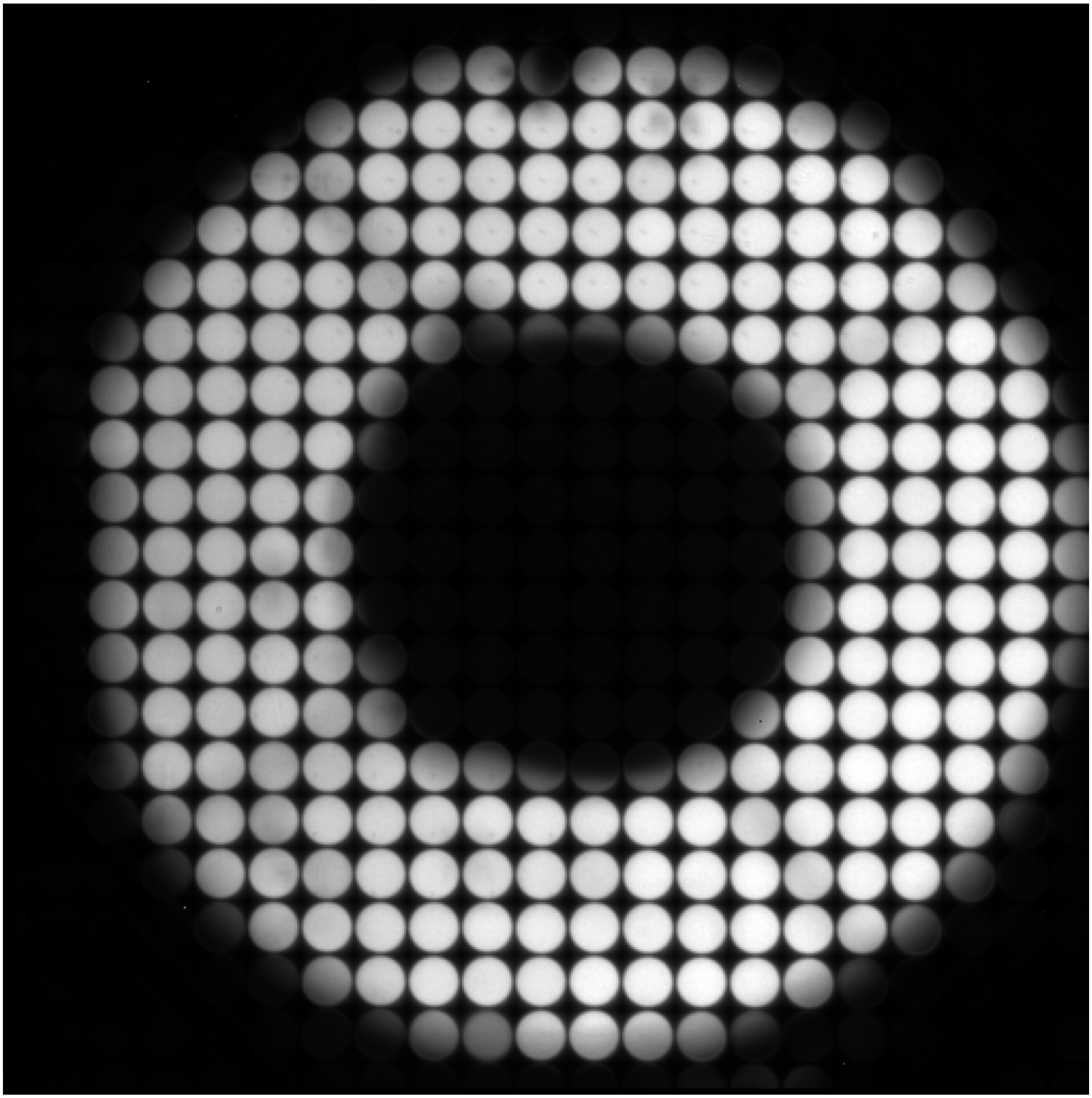


Figure 3: a WFS image taken with the telescope pointing at the dome flat field screen. Each lenslet is producing an image of the WFS 11 arcsec diameter entrance aperture using light from the 150 mm square area of the telescope primary mirror onto which the lenslet maps.

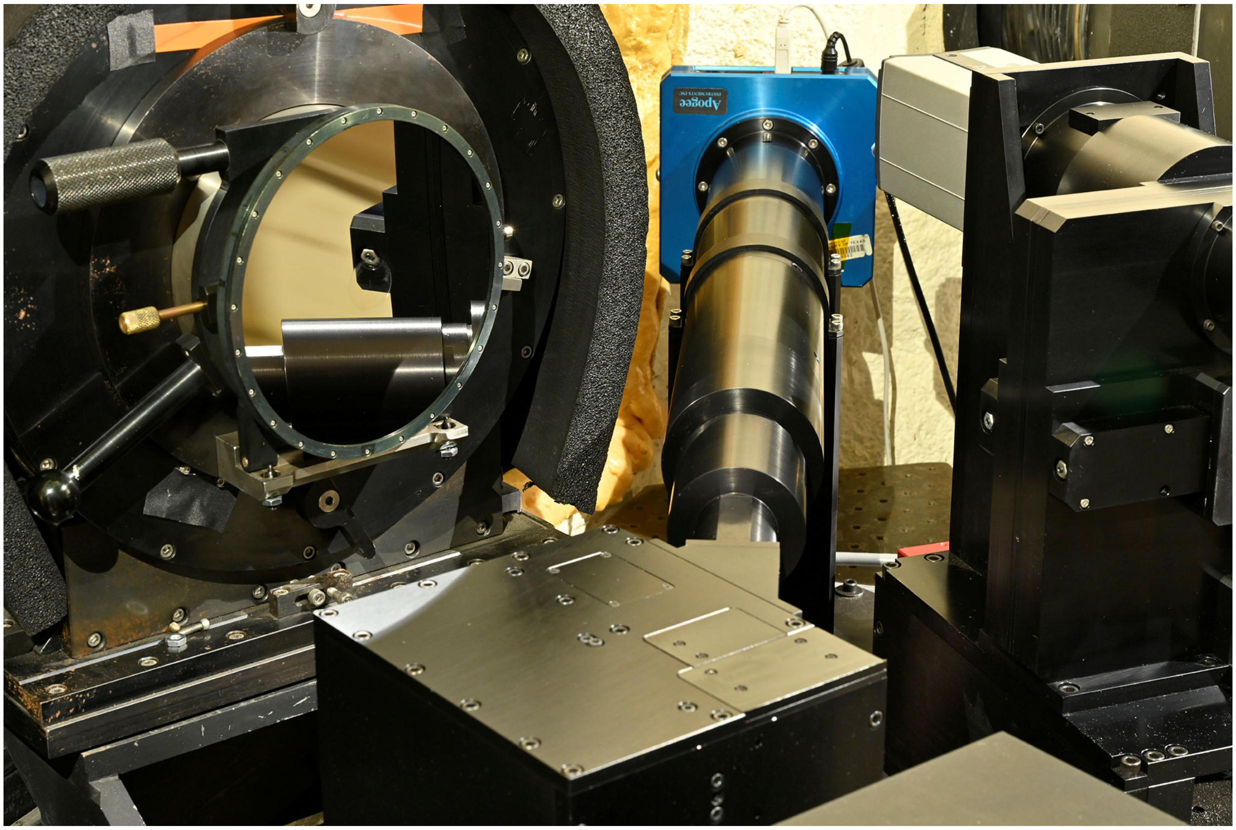


Figure 4: the top of the WFS Feed box in shown lower front center with both its probes retracted. The WFS itself is the cylindrical barrel (black) and WFS detector (blue) running away from the Feed Box toward top center.

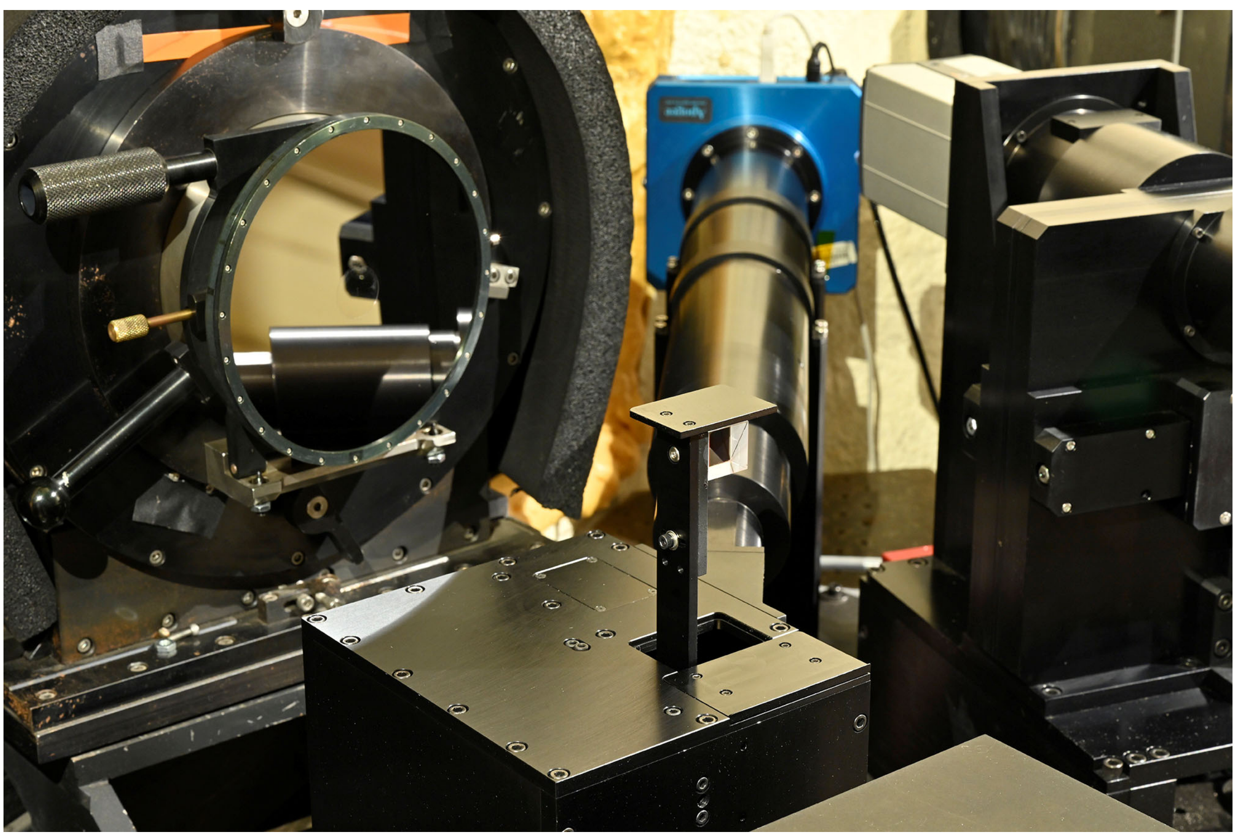


Figure 5: the WFS probe is shown inserted onto the optical axis of the telescope to pickoff the central 25 arcseconds. The beam splitter cube can be seen.

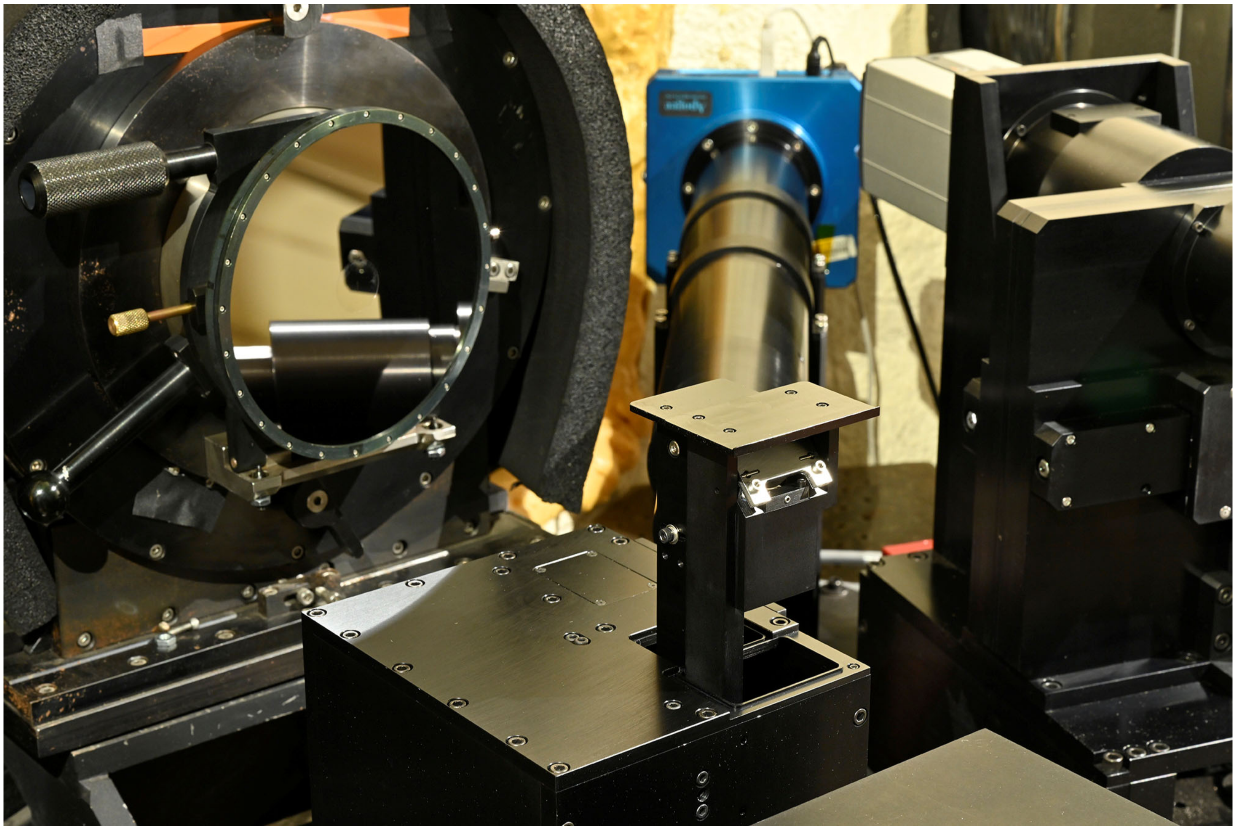


Figure 6: the reference star probe is shown feeding the WFS probe.

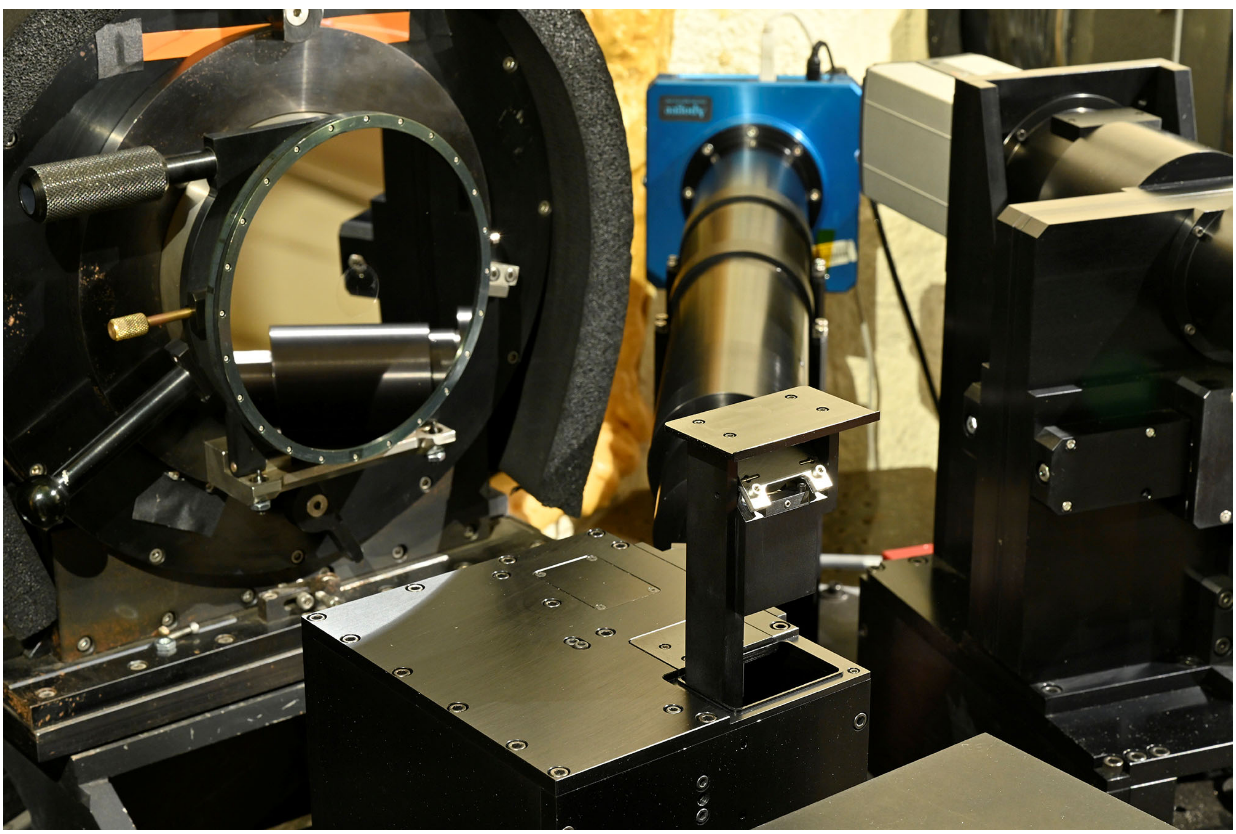


Figure 7: the reference star probe is shown inserted onto the telescope optical axis to image the reference star onto the TS2 slit.

3 Quick start guide

Under the normal observing conditions that an observer should anticipate, the following procedure can be used for focusing the telescope with the WFS.

- During afternoon setup of the spectrograph, start the program ts2*wfs*. There is a blue *Launcher* (icon) on the task bar for this purpose. A main image display window and an *Instrument* window (figure 8) will open. Program ts2*wfs* functionality is heavily based upon the guider program *tsgdr*.
    - The *DarkSub* button on the image display window should normally be selected (red). This subtracts a dark image of matching integration time from WFS images. The dark images comes from an image library.
    - The *Clip* presets in the *View Setup* window are useful for suitable image display, and a *Clip* of 95% is recommended.
    - For thoroughness during afternoon setup, see sections 5.1 and 5.2
- To focus during observing, both program ts2*wfs* and the autoguider program *tsgdr* are used at the same time. Use *tsgdr* to acquire a star onto the normal guiding fiducial centered on the slit, and start autoguiding.
- Make sure the WFS reference star is out of the optical path. The *Out* position indicator light should be *Green* in the *REF* panel of the *Instrument Control* window.
- In the ts2*wfs* *Instrument Control* window, left mouse click the *In* button in the *WFS* panel of the window. Wait for the *Green* position indicator light to illuminate. This inserts a pickoff into the optical path that sends 90% of the telescope light to the WFS and allows 10% of the light to go to the guider in the usual way. The guider image of the star (in the *tsgdr* image window) will dim by a factor of 10, and may require a less dense guider neutral density filter.
- Insert the iodine cell *IF* the science observations will be through the I2 cell. This is done from the *tsgui*. There is a significant telescope focus offset between the I2 cell being in and out of the optical path.
- Select a neutral density filter from the right column of the *TS2 WFS Instrument* window to prevent the spots saturating. In typical seeing the filter attenuation will be approximately (8 – V) magnitudes, where V is the magnitude of the star. Stars fainter than V ~8 use the *0.0 mag* filter
- Except for the very brightest stars (V<~2), use the *25 sec* integration time button to take the wavefront image (figure 9a). Long integration times have the needed benefit of averaging out image motion of the spots relative to each other.
    - If the spots are saturated, a popup window is displayed with a saturation warning, and the WFS image has to be retaken with a denser WFS neutral density filter.
    - Other integration times can be specified in the main *ts2wfs* window, and then an image can be taken with the *Snap* button. Four preset integration times are available in a row of buttons under *Snap.*
- wait for the integration to finish and for the image to readout. An integration and readout progress bar indicator is in the bottom section of the ts2wfs image display window.
- At the end of readout the *Focus* button in the *TS2 WFS Instrument* window will turn red indicating computation activity (figure 9b). Wait the approximately 6 seconds for the focus calculations to take place, ending when the *Delta (Focus)* and *Target (Focus)* values are reported in the *TS2 WFS Instrument* window. Note that the WFS probe must remain inserted for the *Focus* calculation to take place automatically. For star of V>~12 the focus routine can fail for reasons including cosmic rays in the image being brighter than the spots. A cryptic popup window alerts the observer to the failure. The observer has several options:

- The *30 sec M* button in the *TS2 WFS Instrument* window can be tried. It takes 3 integrations of 10 seconds each, and median combines the images to eliminate cosmic rays.
- Use the *Nearby BSC Stars* option in the TCS *Next* menu. Try and choose a star fainter that V~5.5 that is within about 1 to 1.5 degrees from the program star. The HJST should auto slew to the star with a *Go Next.* Focus on the bright star then auto slew back to the program star. At high declinations, try and select stars of similar RA.

- If the *Update* button has previously been selected, turning it red (figures 8 & 9), the telescope focus will be changed automatically, ending when a popup window reports the results of the focus operation (figure 9c).
  - If *Update* is not selected, manually change the telescope focus by either the *Delta (Focus)* amount, or, to the *Target (Focus)* value. The recommended focus procedure is to set the focus with an increasing focus value. If the *Delta* is negative, decrease the focus value to ~300 below the target value, then increase the focus value back up to the *Target* value. Try to set the focus value to within approximately +/- 15 focus units.
- In the *TS2 WFS Instrument* window, left mouse click the *Out* button in the *WFS* panel of the window. This retracts the WFS pickoff from the telescope light path, and lets all the telescope light reach the slit.
- Other potentially useful information is in the section 4 *Useful information to know.*

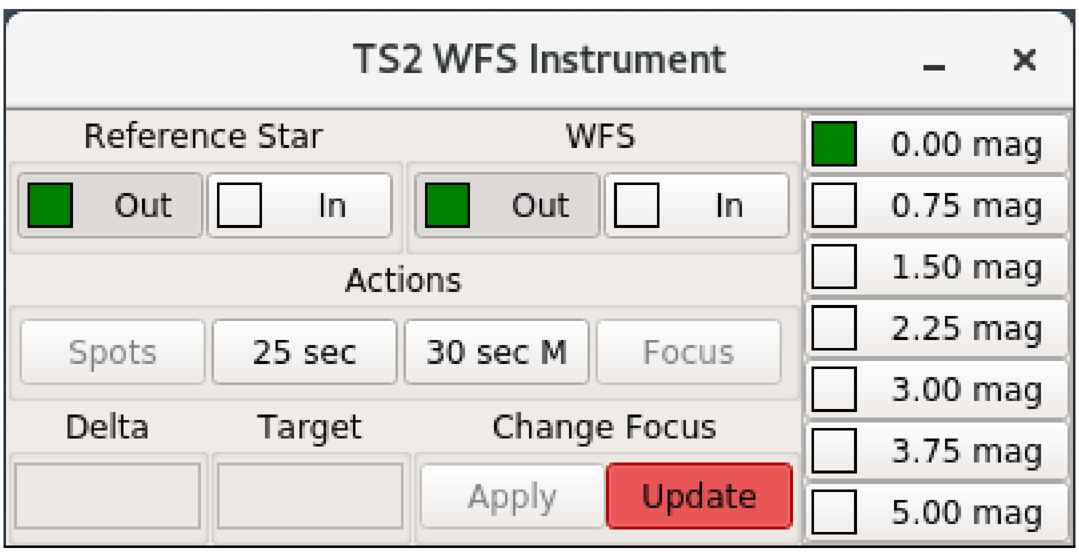
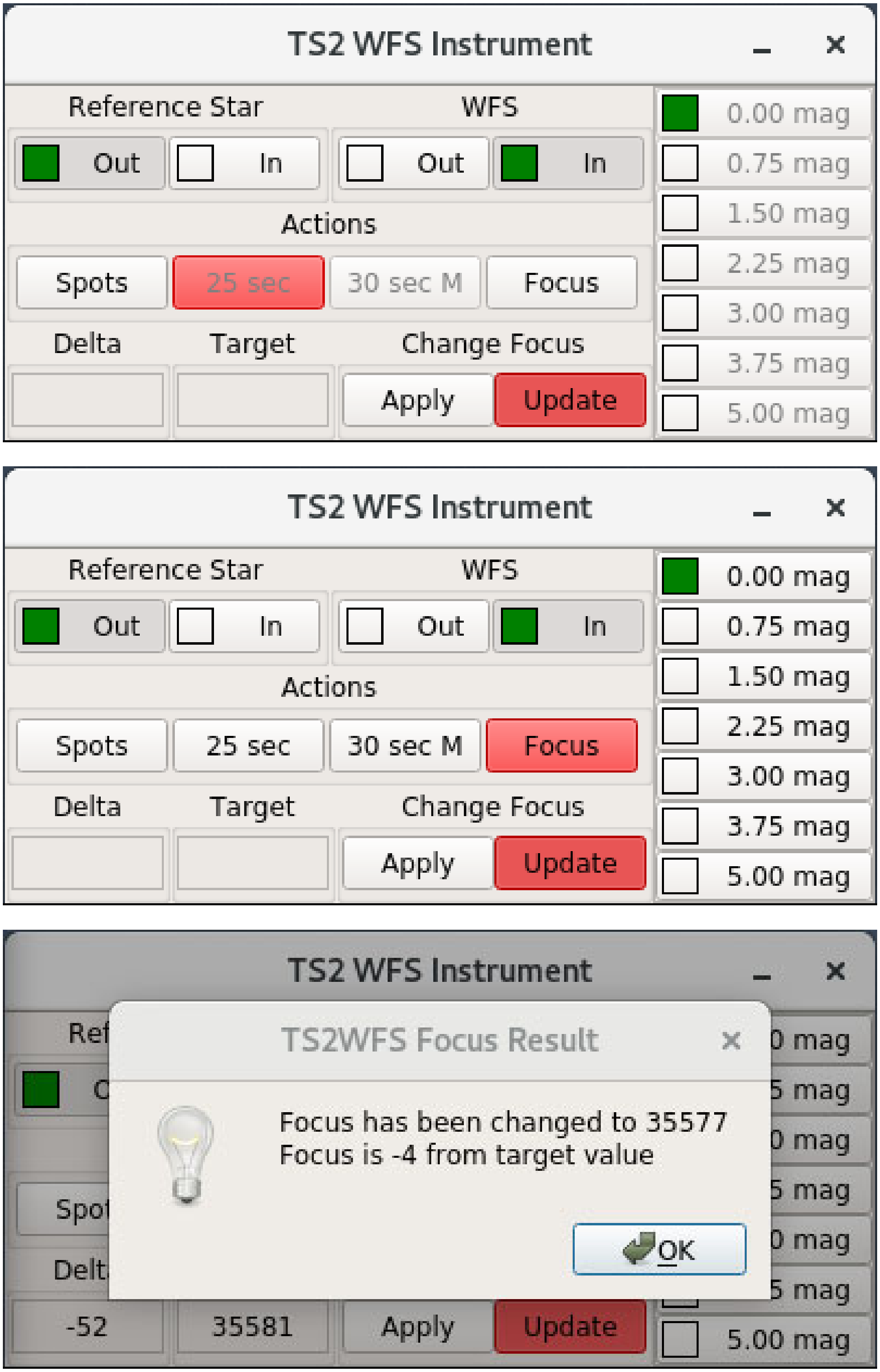


Figure 8: the *TS2 WFS Instrument* window of the *ts2wfs* software. The reference star probe is inserted and retracted with left mouse button clicks on the buttons under *Reference Star*, and the WFS pickoff is inserted and retracted with the buttons under *WFS*. The green indicator lights report *measured* positions of the probes. The reference image is processed by the *Spots* button as an engineering or instrument support process. The WFS image of a star is being processed when the *Focus* indicator is red, and the results from the *Focus* action are reported in the *Delta (Focus)* and *Target (Focus)* reporting panels. If *Update* has previously been left mouse button clicked, turning the button red, then if the TCS is running, the telescope focus is automatically changed after Focus has run. The *25 sec* integration time button is recommended for WFS data taking, and can be used on bright stars by selecting an appropriate neutral density filter. There are seven neutral density filters, selectable in the right hand column, with attenuations given in stellar magnitudes. The ND filter attenuation will be approximately (8 – V) magnitudes, where V is the magnitude of the star. The *Apply* button can be left mouse button clicked to change the telescope focus if the TCS is running, and if *Update* is not selected.



Figures 9a, 9b, and 9C: the *TS2 WFS Instrument* window at three stages of the focus procedure. Top shows a 25 sec integration in progress through the 0 mag ND filter on a faint star. Middle shows the focus being calculated following the image readout, and bottom shows the result after the telescope focus was changed automatically due to the *Update* button having been selected.

4 Useful information to know

There are many factoids that might be of interest or use to observers and support staff. Here are some of those facts loosely organized in categories.

WFS bandwidth

- The WFS uses a SDSS r' filter (550-700 nm) for bandwidth limiting. This is because the internal reference star light source is a 633 nm LED, and the r' filter centers the bandwidth for the star on the reference wavelength.

Telescope focus

- The telescope is focused by moving the secondary mirror axially toward or away from the primary mirror
- A telescope focus encoder measures the axial position of the secondary mirror, and the position is reported as the focus value on the telescope hand paddles and on the telescope control system (TCS) GUI.
- A positive change in the focus encoder value moves the secondary mirror away from the primary mirror.
- As the telescope cools and thermally contracts during a typical night, the focus value will need to increase to keep the separation between primary mirror and secondary mirror fairly constant (focus also has a weaker dependence upon the changing path lengths to the other telescope coude mirrors and the slit).
- It is best to set the focus with the focus value increasing. This moves the secondary mirror up against gravity, allowing gravity to preload the motion for more deterministic moves.
- WFS data has shown that the telescope focus changes depending upon where the telescope is pointing, by up to ~400 focus encoder counts. This behavior is more apparent for significant changes in zenith angle, and for significant changes in the *roll* of the telescope tube, relative to the gravity vector, at the same zenith angle.

WFS focus performance

- On a typical night of reasonable seeing, pre WFS methods allow the focus position to be determined to within approximately +/- 100 focus units. In poorer seeing the focus error might be +/- 200 focus units
- With an integration time of 25 seconds, the WFS focus quality is fairly insensitive to the seeing, and the focus error from the WFS will typically be at or below +/- 10 focus units.
- If the WFS integration time is too short, image motion will make the WFS spots move around relative to each other, degrading the wavefront fit. Longer integrations average out the spot motion which is important because the centroids of the spots is the data reduced from the image frames.
- There is a scale factor between the Zernike focus coefficient and the required change in the telescope focus. The current value of the scale factor achieved a telescope focus that delivered 0.7 arcsec FWHM image quality during commissioning in a period of good seeing.

WFS use with the iodine cell

- The iodine cell has an entrance window and an exit window that are each 6.35 mm thick. When the iodine cell is inserted the extra optical path length through the cell windows moves the axial position of the telescope focus by about 4 mm. Therefore, the telescope should be focused through the iodine cell with the WFS if the iodine cell is to be used for precision radial velocity observing.

WFS personality

- The WFS camera has a CCD with fairly poor image quality. Specifically, the CCD has quite a few bright pixels. The wavefront fitting software can crash when a hot pixel within a lenslet image is brighter than the image of the star. This was seen to happen for V >~ 9 mag, and therefore the *wfs* software subtracts a master dark image of appropriate integration time, selected from a library of master dark images. This dark correction allows the WFS fit to be quite reliable to the limit tested of V ~ 13 mag.
- Cosmic rays accumulate on the WFS detector in longer integration times. Some cosmic rays can be much brighter that the WFS spots for faint stars, and this can cause the WFS fit to fail. Try another integration if this happens, or move to a nearby bright star (V~6) to focus.

5 **The reference image**

The WFS data is not absolute in nature, and must be measured relative to a reference that represents a plain (unaberrated) wavefront. The WFS Feed includes a reference star for presenting an unaberrated wavefront to the WFS for making a reference image. An image of the reference star is made with the WFS, as shown in figure 10, and the spot positions in the reference image are the spot positions in the absence of aberrations.

The reference image is expected to be stable over a long period of time, but does have a winter to summer variation driven by ambient temperature. The variation has a sub arcsecond effect of telescope focus, and the effect has yet to be modelled out.

Currently there is a single reference image and it is used by all observers. Any observer can make a new reference, and that new reference will replace the previous reference. Observers generally do not make reference images, as that is typically a task for the Instrument Scientist or Observing Support.

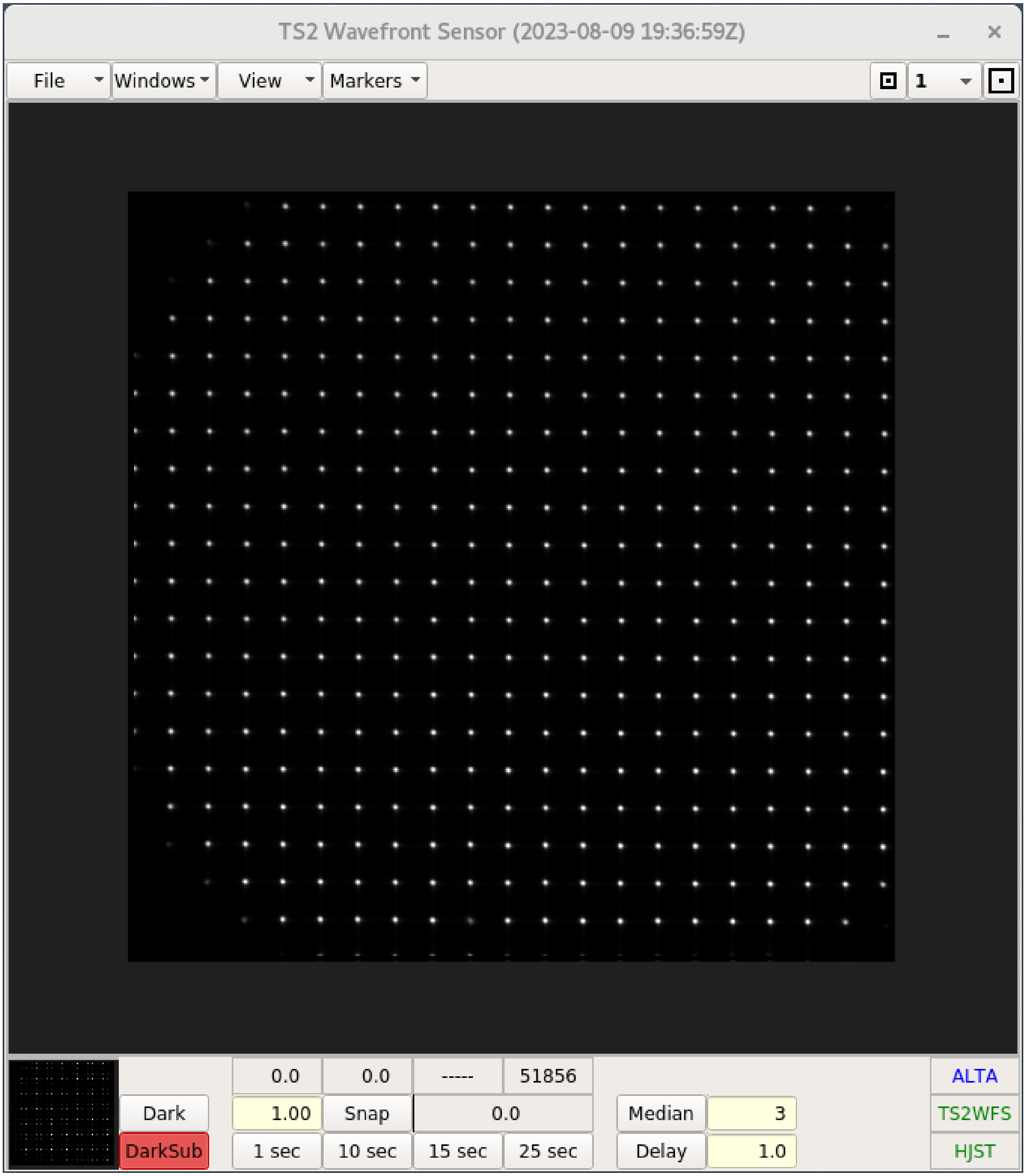


Figure 10: a WFS image of the reference star. These spot locations are those of a plane wavefront at the corresponding position in the pupil.

5.1 Checking the reference star

Viewing the reference star with the autoguider program *tsgdr* is one check on the status of the WFS instrumentation. This is the procedure.

- Ensure that the TS slit room is dark, and that the slit is not being illuminated, for example, by the Solar Port or Calibration System.
- From the *wfs* software *Instrument Control* window, insert the REF probe, and make sure the WFS probe is retracted.
- Change the guider bandpass filter to the *400-700 nm* filter (or any filter that passes the 633 nm light of the reference star), and change the guider neutral density filter to *Open*.
- Take a guider image with a 1 second integration time to confirm that the reference star is centered on the slit to within several guider pixels (see figure 11). Report the status if it is not centered.

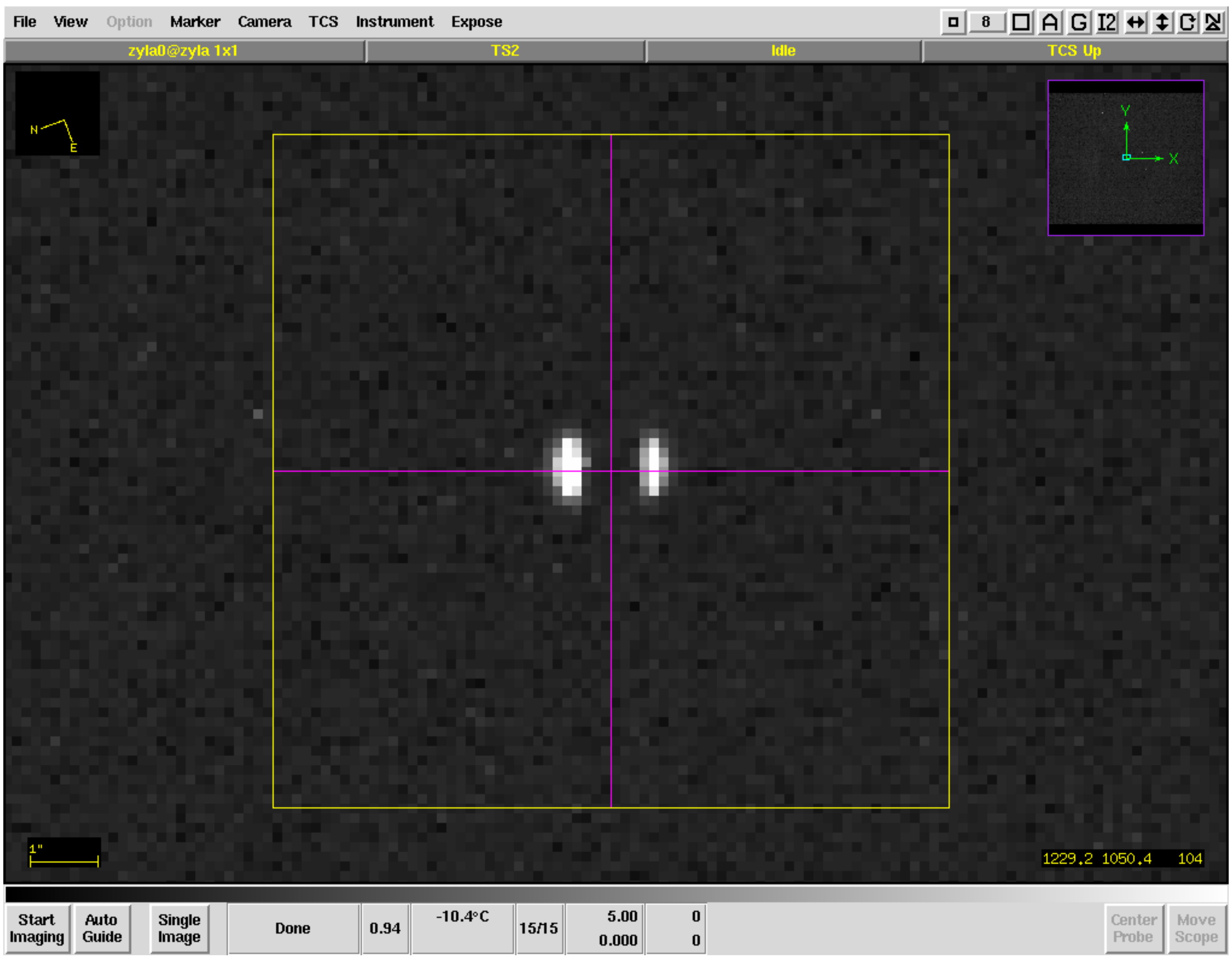


Figure 11: an image of the reference star on TS23 slit #4, as seen with a previous version of the autoguider program *tsgdr*. A typical decentering error is visible. The error seen here of ~1 guider pixel, or, ~0.15 arcseconds is quite acceptable given the 11 arsecond entrance aperture of the WFS.

5.2 Checking the reference image

The validity of the reference image can be check with the following procedure

- Ensure that the coude slit room is dark, and that the slit is not being illuminated, for example, by the Solar Port or Calibration System
- The Telescope Control System monitor program needs to be running in the background, as is normally the case, but the tcsgui does not need to be running.
- From the wfs *Instrument Control* window, insert the *REF* probe, and insert the *WFS* probe.
- Again from the wfs *Instrument Control* window, set the WFS neutral density filter to the *0.00 mag* filter.
- Take a 1 second WFS integration via the *Single Image* button at the bottom of the *wfs* image display window. The brightness of the reference star has been set so that a 1 second integration gives peak spot brightnesses in the mid 50-thousands DU.
- Confirm that the maximum intensity is below saturation at 65,535 DU, and ideally, that the typical spot maximum is in the mid 50-thousands DU.
  - In the image display, zoom in on a region of spots so that individual pixels can be seen in the spots, and by mousing onto the central pixels of spots, confirm that the maximum intensity is below saturation at 65,535 DU, and ideally, that the typical spot maximum is in the mid 50-thousands DU. Adjust the integration time and repeat if the spots are saturated or too weak. Report finding peak brightness that are not 50-something thousand DU.
- Left mouse click the *Find Focus* button in the *Instrument Control* window and wait about 28 seconds (on computer atlas) for the wavefront calculations to take place.
- Confirm that the *Delta Focus* is a very small value, typically less than 10 focus units.
- You can also click the *Show Wave Info* button in the *Instrument Control* window, and confirm that the column 2 values for Z04 and higher are well less than 0.1 waves.
- If the conditions in the two previous bullets are met, the reference image is good. If the conditions are not met, a new reference may be needed.
- Finish the reference image check by retracting the REF probe and the WFS probe.

5.3 **Making a new reference image**

A new reference image can be made with the following procedure. It should be noted well that ***the*** reference image is used by ***all*** users of the WFS until a new reference image is made. It is important that the reference image is made well.

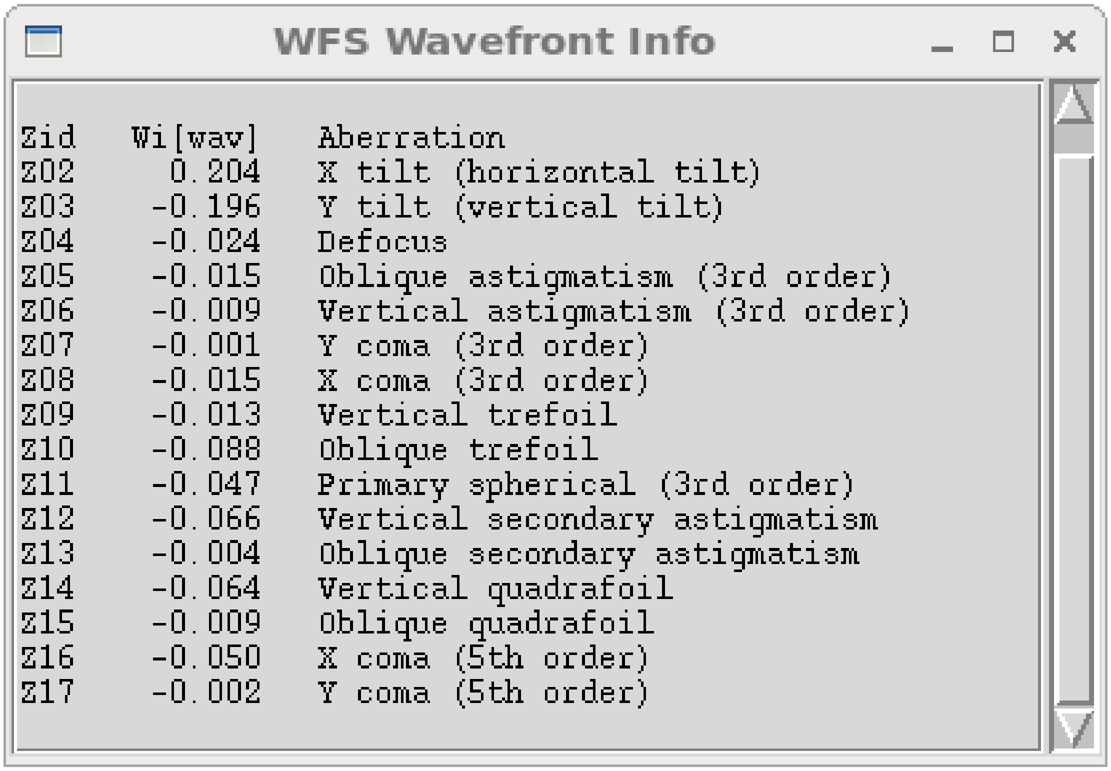
- Ensure that the TS slit room is dark, and that the slit is not being illuminated, for example, by the Solar Port or Calibration System.
- From the *wfs* software *Instrument Control* window, insert the WFS probe, and retract the REF probe.
- Change the guider bandpass filter to the *400-700 nm* filter (or any filter that passes 633 nm light), and the guider neutral density filter to *Open*.
- Take a guider image with a 1 second integration time to confirm that the reference star is centered on the slit to within several guider pixels (see figure 10). Continue if it is centered. Report the status if it is not centered, and stop.
- From the *wfs* software *Instrument Control* window, insert the WFS probe (and leave the REF probe inserted).
- Take a 1 second WFS integration via the *Single Image* button at the bottom of the *wfs* image display window. The reference star brightness has been set so that 1 second is the right integration time.
- In the image display, zoom in on a region of spots so that individual pixels can be seen in the spots, and confirm that the maximum intensity is below saturation at 65,535 DU, and ideally, that the typical spot maximum is in the 50 thousands DU. Adjust the integration time and repeat if the spots are saturated or too weak. Report the need to use an integration time other than 1 second.
- Left mouse click the *Find Spots* button in the *Instrument Control* window.

This completes the making of a new reference image. The next step checks the new reference image, and is a continuation of the above sequence of actions

- Take a 1 second WFS integration via the *Single Image* button at the bottom of the *wfs* image display window
- From the wfs *Instrument Control* window, retract the *REF* probe. The will make the *Find Focus* button become active
- Left mouse click the *Find Focus* button in the *Instrument Control* window and wait about 28 seconds for the wavefront calculations to take place.
- Confirm that the *Delta Focus* is small, typically less than 10 focus units
- From the wfs *Instrument Control* window, retract the *REF* and WFS probes

6 **Display of wavefront information**

The measured wavefront as represented by the first 17 Zernikes can be viewed in a window as shown in figure 11. Zernike Z01 is not reported as it is simply the axial piston of the wavefront, and doesn't hold any wavefront shape information.



WFS Wavefront Info

Zid	Wi[wav]	Aberration
Z02	0.204	X tilt (horizontal tilt)
Z03	-0.196	Y tilt (vertical tilt)
Z04	-0.024	Defocus
Z05	-0.015	Oblique astigmatism (3rd order)
Z06	-0.009	Vertical astigmatism (3rd order)
Z07	-0.001	Y coma (3rd order)
Z08	-0.015	X coma (3rd order)
Z09	-0.013	Vertical trefoil
Z10	-0.088	Oblique trefoil
Z11	-0.047	Primary spherical (3rd order)
Z12	-0.066	Vertical secondary astigmatism
Z13	-0.004	Oblique secondary astigmatism
Z14	-0.064	Vertical quadrafoil
Z15	-0.009	Oblique quadrafoil
Z16	-0.050	X coma (5th order)
Z17	-0.002	Y coma (5th order)

Figure 12: the *WFS Wavefront Info* window is shown, that can be launched from a button on the *Instrument Control* window. The *Noll Sequential Indices* notation is used in column one for naming the Zernikes. Column two gives the amplitudes of the various Zernikes in units of wavelengths, where the wavelength is 633 nm for the TS2 WFS. Column 3 gives the common name of the optical aberration that corresponds to the Zernike. For example, what is commonly called *Spherical Aberration* is 3rd order spherical aberration, and is Z11. The WFS software uses Z04 to determine the telescope focus via a linear function.

7 Care of the WFS hardware

- Do not put anything on top on the WFS feed box. Inserting the probes might knock light objects off the top, and those objects could damage the probe optics while falling. Heavy objects might stall the motion of the probes and could damage the probe precision drive mechanisms.
- Do not push on the probes either vertically and laterally. They are small precision mechanisms and can be damaged by inappropriate handling.
- The top of the WFS feed box should remain completely black. The telescope light skims the top of the box and could cause stray reflected light if the surface is not black. There is a knife edge on the leading edge of the box (on the reference star probe) to shadow the top of the box from the incoming light that falls outside the field mirror.
- Do not CO2 clean the WFS optics. Some optics are glued on to their mounts and sudden differential thermal contraction might break the glue joints
- With both WFS probes *retracted*, monthly cleaning is recommended of the top of the WFS Feed Unit. This should be done with a lightly damp, lint free cloth. Cleaning helps prevent dust accumulation that can blow into the unit when probes are deployed.
- The brightness of the reference star can be adjusted via a rheostat behind a removable cover on the lower east side of the WFS. The brightness is set so that a 1 sec reference star integration with no ND filter is properly exposed.
- The reference star can be viewed and checked for focus and alignment on the slit with the Slit Viewer. A ghost image will also be seen.

8 The WFS engineering

8.1 Optics

The optical design work was done with Zemax. The calibration work was done with RayTrack on computer Crux II. The files will be added to the Inventor Vault.

8.2 The mechanical design

The mechanical design work was done with Inventor, and is in the Inventor Vault. This includes the model and all the part drawings.

8.3 The control electronics

The WFS control electronics are installed in the 2018 controller that is located in the spectrograph ante room. All schematics were done with OrCAD, and will be added to the Inventor Vault.

8.4 The Project Group

The WFS system was designed and built by the following project group

- Brian South, Mechanical Engineer
- Joseph Strubhar, Mechanical Engineer
- Doug Edmonston, Electronics Technician
- Sam Odoms, Senior Software Engineer
- Hanshin Lee, Research Scientist
- Gordon Wesley, Mechanical Engineer
- Rupert Ruiz, Machinist
- Kenneth Hope, Machinist
- Johnny Goertz, Machine shop Supervisor
- Phillip MacQueen, Senior Research Scientist

The *backend* of the WFS was built in 2011, along with a cassegrain Fabry *frontend,* for testing the HJST f/9 optics. The f/9 frontend and its reference star are in storage in the Austin CCD lab, and can still be used for f/9 testing. The cassegrain configuration mounts on DIAFI instead of the CCD detector system.