NFIRAOS AO Calibration Plan Update

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ABSTRACT

This paper presents some new developments related to the NFIRAOS calibration plan. These developments includes changes in the calibration hardware, including a new calibration source set-up, as well as more details calibration tasks, such as the calibration of the star selection mechanism in the NFIRAOS Pyramid WFS, which serves as truth WFS in LGS mode and as high-order WFS in NGS mode.

Keywords: Adaptive optics, calibration

1. INTRODUCTION

The Narrow Field IR Adaptive Optics System (NFIRAOS) is the first light facility adaptive optics (AO) system for the Thirty Meter Telescope (TMT). The NFIRAOS project is currently at the pre-production stage [1]. NFIRAOS is a multi-conjugate AO system. It has two large deformable mirrors, conjugated to 0 (DM0) and 11.8km (DM11) respectively, with a total of more than 7000 actuators. For most observations, these deformable mirrors will be driven from the measurements of six 60x60 laser guide star (LGS) wave-front sensors (WFSs) at a frame rate of 800Hz, aided by a slow moderate order natural guide star (NGS) pyramid WFS (PWFS), which is used as Truth sensor. However, when the science target is a bright source and the required field of view is small, the lasers are turned off and the DMs are only driven by the PWFS used in high-order, high-speed mode. The AO-corrected light is fed to one of three science ports. The NFIRAOS top-level diagram shown in Figure 1.

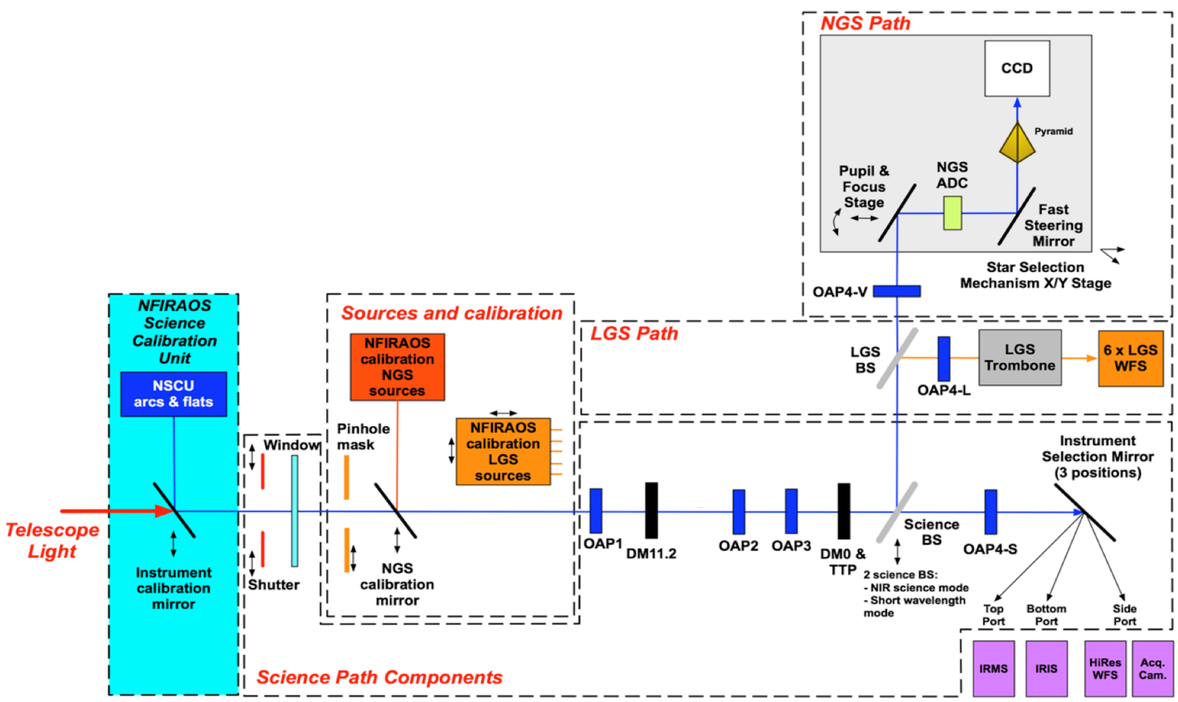

Figure 1: NFIRAOS top-level block diagram

The NFIRAOS calibration plan has already been presented in 2016 [2]. In this paper we provide an update to this plan, mainly focusing on recent changes to our calibration tools (Section 2) and details on calibration procedures (Section 3), especially the calibration and operation of the star selection mechanism in the PWFS path.

2. CALIBRATION TOOLS

2.1 NFIRAOS Sources Simulator (NSS)

The NFIRAOS Source Simulator (NSS) provides artificial sources, which are critical for calibrations. The NSS is composed of:

- A deployable focal plane mask (FPM), with pinholes located all over the NFIRAOS 2' FOV. When the FPM is back-illuminated by the NSCU, each pinhole becomes an artificial source.
- A single broadband source simulating a natural guide star (NSS_NGS), attached to the bottom of the FPM unit and deployable at any location along the Y-axis (orthogonal to the TABL). This source has three intensity settings: bright, moderate and faint. The faint setting is such that the source can be imaged on the IRIS science detector, while the moderate setting is suitable for the IRIS IFS. The bright setting is such that the source provides high enough flux on NSEN HRWFS to achieve high SNR measurements.
- A deployable asterism of six sources simulating the NFIRAOS laser guide star asterism (NSS_LGS).

The FPM and the NSS_NGS are deployed at the NFIRAOS entrance f/15 focal plane where the plate scale is 2.18mm/arcsec on the sky.

All the sources are designed so that they emit a cone of light larger than f/15, large enough so that the beamprint at DM0 is larger than the aperture mask. As a result, the DM0 aperture mask defines the pupil when the NSS is in use. This mask is 317 mm in diameter, and therefore the equivalent beam is ~f/14.2.

Internal NGS source (NSS_NGS)

The NSS_NGS is a 10um source that can be deployed on-axis. It is attached to the bottom of the FPM and uses the same deployment mechanism as the FPM, which is a carriage on a rail along the Y-axis (orthogonal to the NFIRAOS bench). Therefore, it can in principle be positioned at any location on the Y-axis, although we currently have no use case where the NSS_NGS is used off-axis. Similarly, it could be moved by +/-1mm along the X axis with the mechanism used to dither the FPM along the X-axis.

The NSS_NGS is broadband, and its expected magnitudes in the bright setting in the bands of interest are given in Table 1.

Band	Photon flux	ZeroPoint	Magnitude
PWFS (610nm – 785nm ~ R-band)	1.8e11 ph/s	13.5e9 ph/s/m^2	R=4.3
Z' band (790nm – 1000nm)	4.0e11 ph/s	5.63e9 ph/s/m^2	Z'=2.5
J band (1150nm – 1350nm)	4.7e11 ph/s	3.22e9 ph/s/m^2	J=1.7
H band (1500nm – 1800nm)	5.0e11 ph/s	2.82e9 ph/s/m^2	H=1.5
K band (2000nm – 2400nm)	4.0e11 ph/s	1.51e9 ph/s/m^2	K=1.1

Table 1: Magnitude of the NSS_NGS at different bands

The NSS_NGS is very bright, in order to provide good SNR on the NSEN-HRWFS (see section 2.2 below) and on the PWFS. It is too bright to be imaged by IRIS without saturating its detectors.

The NSS_NGS is produced by a 10um pinhole. Diffraction is 10.5um at R-band, 18um at J-band, so the source is diffraction limited in the NIR and slightly resolved in the visible.

The NSS_NGS has been recently scaled down from the original 17-source asterism [2], some of which adjustable, to a single source.

Internal LGS sources

The NSS includes 6 artificial LGS sources, mounted on a stage that enables them to move along the optical axis to simulate various altitude ranges. They are 0.8" in diameter. Note that the NSS NGSs will still be visible when the LGS are deployed (only very partial vignetting of the NGS light).

Deployable focal plane mask

A focal plane mask (FPM) can be deployed at the entrance focal plane to generate a dense array of calibration sources across the entire 2 arcmin FOV. It is illuminated by the NFIRAOS Science Calibration Unit (NSCU) located in front of NFIRAOS. The sources are 25um in diameter or 11mas on the sky. A few sources are 250um in diameter to provide higher SNR on the HRWFS, which is attached to one of the science ports for diagnostic. The layout of the pinholes has been changed recently and is shown in Figure 2 and in Figure 3.

The FPM is illuminated by the NSCU, in such a way that the light emitted from each source overfills the aperture mask on DM0 and is uniform to within 10% inside the aperture mask. In the central portion of the FPM, which corresponds to the FOV of the IRIS science detectors, the sources are separated by 1mm or 0.45 arcsec on sky. For the rest of the 2' FOV, they are separated by 5 times this distance or 2.27 arcsec on sky. In the central region, a few sources are added for calibrating the IFS. The FPM can be dithered to perform astrometric calibrations (see section 3.2) by +/-2mm or +/-0.9". In the central regions, some of the 25um sources are isolated (they do not have neighbors) so that they can be used to evaluate image quality on IRIS without confusion due to crowding (the AO control radius is AO control radius is 0.45" at K, 0.26" at J-band).

The 25um sources from the FPM are actually too large to accurately evaluation image quality at NIR wavelengths (diffraction limit is 9 mas (19 um) at J, 15 mas (33 um) at K). For this kind of assessment, the smaller NSS_NGS must be used.

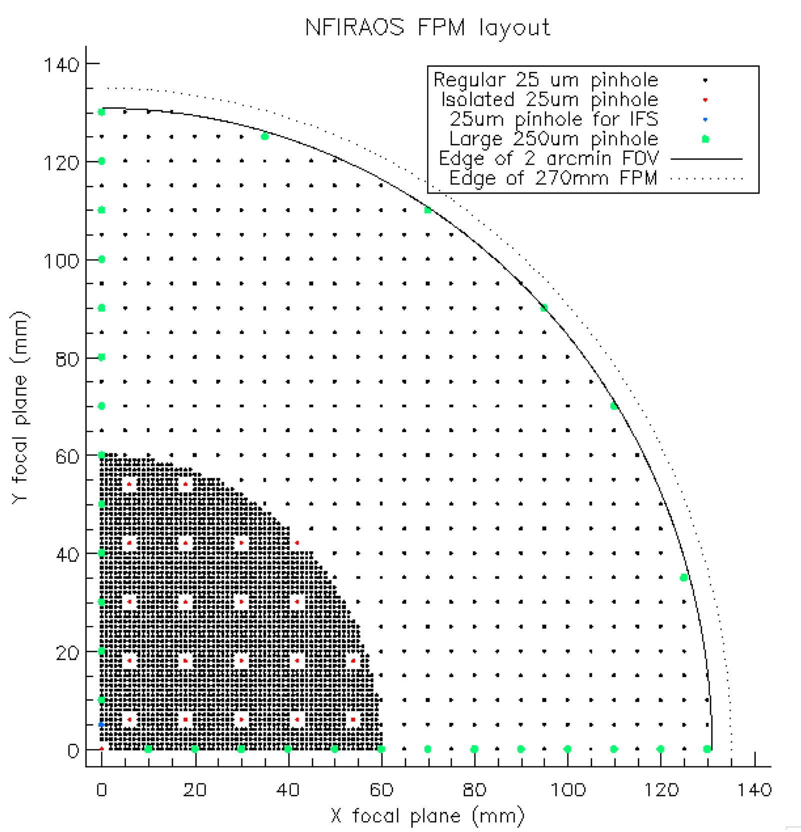

Figure 2: FPM layout for the entire FOV (only one quarter shown)

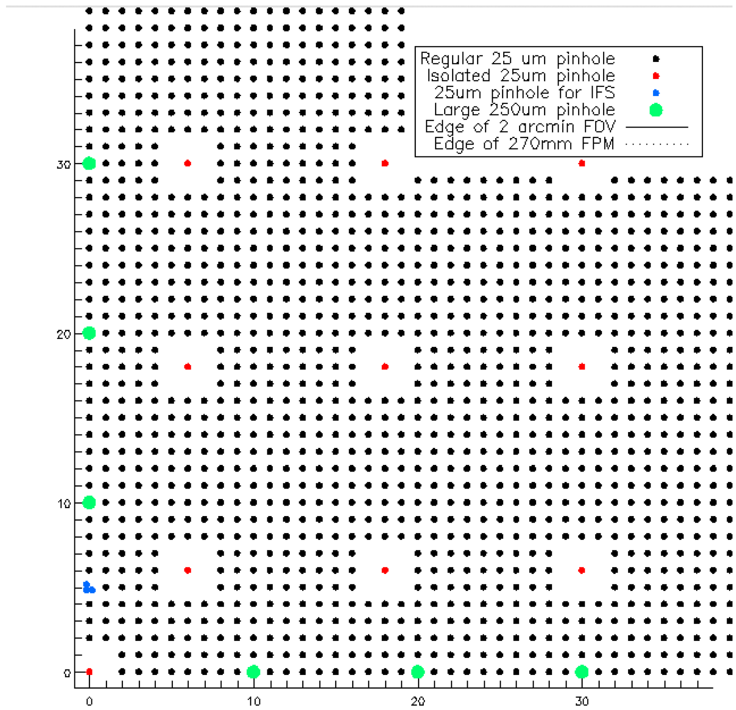

Figure 3: FPM layout in the central region (only one quarter shown)

2.2 NSEN

NSEN, the NFIRAOS Equipment Sensor, is mounted on one of the three instrument ports, and as such, acts as an instrument. NSEN contains: a high-resolution WFS (NSEN-HRWFS), a diffraction limited camera (NSEN-DLC) and possibly an acquisition camera. The sensors are mounted on an X-Y-Z stage to allow positioning them at any point in the NFIRAOS 2 arcmin FOV. Diffraction-limited calibration sources are located just outside the FOV, at the end of the X and Y stage travels.

NSEN-HRWFS

The NSEN-HRWFS is a visible light high-resolution Shack-Hartmann WFS, and is nominally a HASO3-128 (128x128 sub-apertures) from Imagine Optic. This commercial product is able to measure wave-front errors with very high accuracy (λ/100 RMS absolute accuracy, λ/150 RMS accuracy when calibrated against a reference wave-front), very good repeatability (<λ/200 RMS) and high dynamic range (>1500λ of tilt). Measurements can be obtained at a frame rate of up to 7.5Hz. In nominal configuration, the NSEN-HRWFS will operate after the science beam-splitter, in the 800nm – 1000nm wavelength range.

The HRWFS is mounted on an X-Y-Z stage and is able to patrol the full 2' FOV with excellent accuracy, and therefore access all the sources from the FPM. The speed requirement is that the full 2' field should be traversed in less than 30 seconds.

The HRWFS includes a collimator to re-image NFIRAOS exit pupil onto the lenslet array. According to the NSEN preliminary design, the NFIRAOS pupil will be imaged on the lenslet array in a 13.9mm diameter. Since each lenslet is a 114.13um x 114.13um square, this corresponds to about 122 lenslets. The focal length of each lenslet is f=4.6mm and the detector is a 2048x2048 CCD with p=7.4um/pixel. The plate scale at the detector is therefore (p/f)*(d/D)=0.15 arcsec on sky / pixel (D=30m), and each lenslet has ~15.4x15.4 corresponding pixels.

The collimator is specified for a 500um operational FOV at the f/15 focal plane. This corresponds to 0.23 arcsec on the sky. The operational FOV size was chosen to be comfortably larger than the 100um repeatability of the X and Y stages, so that, once proper pointing models are in place, acquisition is guaranteed to be successful. Within the operational FOV, pupil distortion is very small (< 0.2% across the full NFIRAOS pupil diameter) and wave-front errors are very small (< 20 nm RMS). The total FOV of the HRWFS is limited by a 1.6mm pinhole, corresponding to 0.73 arcsec on the sky. The pinhole size was chosen in order to be able to select a single source from the FPM.

NSEN-DLC

NSEN-DLI is a diffraction limited, 2xNyquist sampled J-band camera. It is mostly use to evaluate the NFIRAOS performance, especially far off-axis, outside the FOV of the science camera.

NSEN Calibration Sources

NSEN is equipped with four calibration sources able to present a flat wave-front (with a wave-front error < 10nm RMS) to the NSEN-HRWFS and to the NSEN-DLC for calibration. The calibration sources are located at each end of the X and Y stage, just outside the NFIRAOS FOV.

2.3 Calibration files

Calibration results are aggregated in several files called calibration files. The repository for the NFIRAOS calibration files is the TMT Configuration Service (TMT CS).

The NFIRAOS calibration files are used either by the NRTC (NFIRAOS Real-Time Controller), by the NCC (NFIRAOS Component Controller) or by the RPG (Real-Time Parameter Generator), which is part of the AOESW (AO Executive Software).

The AOESW maintains a configuration file, which contains a list of references to all the current calibration files. Different sets of calibration files are required e.g. depending on the temperature of operation. The AOESW loads directly the calibration files required by the RPG. As part of the "Configure" command, the AOESW passes to the NRTC and to the NCC the references to the calibration files that these systems need to load.

Table 2 provides some examples of calibration files required by the RPG, the NRTC and the NCC.

RPG calibration files	NRTC calibration files	NCC calibration files
WFS plate scales	DM System Flats	DM flattening maps
Centroid gains / optical gains for the calibration sources	WFS detector flats and darks	DM actuator gain maps / actuator linearization function
CCD noise level	WFS slope offsets and system flats	TTS offsets, gains, and rotation angle
DM actuator influence functions		All pointing models
Experimental Interaction Matrices		
Residual DM-WFS mis-registration models		
Optical distortions between M1 and LGS WFS		

Table 2: Example of calibration files required by the RPG (left) and by the NRTC (right)

The TMT CS maintains the different versions of every calibration file. The AOESW configuration file lists the version of every calibration file that will be loaded for AO operation.

Loading a calibration files involves querying the TMT CS for a calibration file, optionally specifying a version number. The TMT CS responds to the query by providing a pointer (nominally a URL) with which the file can be retrieved.

Saving a calibration file involves invoking a command that allows submitting a file to the TMT CS. When a new calibration file is submitted, the TMT CS returns the version number under which the file is saved.

2.4 NFIRAOS calibration software (CALSW)

The NFIRAOS Calibration Software (CALSW) is responsible for carrying out the NFIRAOS calibrations. Eventually, the functionalities of the CALSW will be integrated into the AOESW, but initially, the CALSW will be written in a higher-level language such as IDL or Matlab, in order to enable maximum flexibility to adapt to unforeseen conditions and easily update the calibration procedures accordingly.

The architecture of the CALSW is summarized in Figure 4.

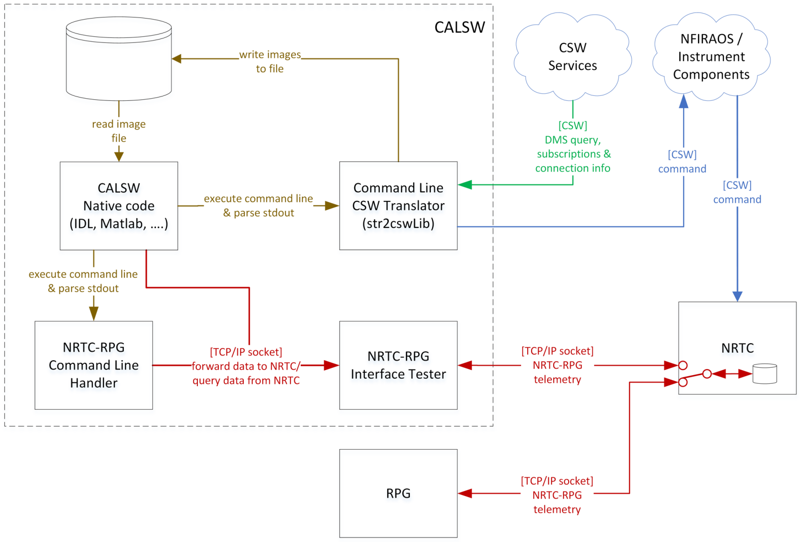

Figure 4: CALSW Architecture

In many instances, the calibration processes is driven by the CALSW but performed through the NRTC. To communicate with the NRTC, the CALSW uses the same communication channels as the RPG, which is part of the AOESW. The CALSW can issue the same commands as the RPG, including setting switches, and closing the AO loops. In addition, the NRTC provides commands that are specifically dedicated to calibration:

- calibModePixel: returns the average of a user-specified number of consecutive WFS images, where the averaging process is started after a user-specified delay.
- calibModeGrad: same as calibModePixel except that the average of the gradient vectors are returned.
- calibModeCmd: same as calibModePixel except that the average of the WC commands are returned
- calibModeWc: forces the RTC to drive the WCs (DMs and TTS) based on commands sent by the CALSW instead of based on the normal real-time pipeline

These commands are very useful for calibration because they can be issued while the loop is closed (open loop measurements can be obtained by "closing" the loop with a gain of 0) and the averaging can be performed at 800Hz. The calibModePixel and calibModeGrad commands can be configured in "trigger" mode. In this mode, the command is triggered by issuing a "calibModeWc" command. This is useful for example when measuring interaction matrices.

The CALSW can also send commands to the NCC, e.g. to configure detectors, switch on/off sources in the NSS, request a measurement from NSEN, etc. It can also send commands to the OIWFS CC to configure the detectors, move the probe arms, move the ADCs, etc. Finally, it can send commands to the IRIS IS to configure the science detector and request an exposure.

A typical calibration task executed from the CALSW is sequenced as follows:

1. Load a default configuration for the NRTC, NCC, OIWFS CC and IRIS IS
2. Instruct the NRTC to listen to CALSW instead of AOESW
3. Modify some configuration files for the NRTC and/or the NCC
4. Inform the NRTC of the output required (through the "calibMode" commands above)
5. Instruct the NRTC to start real-time processing. While the loop is closed, the NCALSW may do any number of the following tasks:
   - Modify some configuration files
   - Read and process an NSEN, IRIS or OIWFS measurements
6. Instruct the NRTC to stop real-time processing,

7. Read and process the NRTC telemetry averages if any of those were requested.
8. Create new calibrations files and submit them to the TMT CS

3. SAMPLE CALIBRATION PROCEDURES

3.1 PWFS Star Selection Mechanism pointing model and pupil location model

Goals and requirements

The PWFS Star Selection Mechanism (SSM) pointing model involves determining X_{PM},Y_{PM},Z_{PM} of one mechanism (pupil steering mirror) and X_{ST},Y_{ST} of another one (X and Y stages carrying the PWFS bench) as a function of the field position of the target. The goal is to be able to bring any target whose field position is known well within the capture range of the PWFS, while achieving proper registration between the DM actuators and the PWFS images. More specifically, for any position in the field, the pointing model should be able to achieve the following two requirements:

1. Bring GS to within 9 mas RMS of the tip of the pyramid anywhere in the FOV
2. The position error between any two positions 30 arcsec or less apart should not be different by more than 2 mas RMS
3. Achieve same DM0 to pupil image registration as on-axis to within 0.04% of pupil diameter

The first requirement is for blind pointing across the FOV. The second requirement is for accurate dithering. The third requirement comes from the desire to limit the required undersizing of the Lyot stop in the science instruement in order to maximize the point source sensitivity.

NCC implementation

Operation mode

During operation, the PWFS SSM pointing model is implemented in the NCC as the “NGS SSM Assembly” as shown in Figure 5. The purpose of this calibration task is to determine the parameters of the “global pointing model” block, and of the “differential offset model” block. For a given GS position, the “differential offset model” allows tweaking the image and pupil positions.

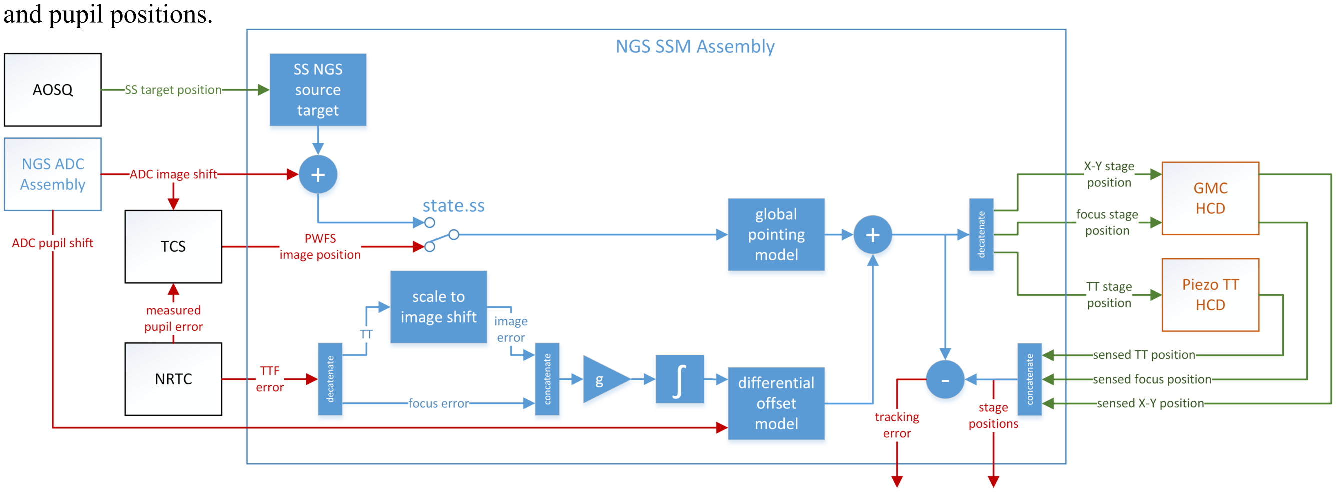

Figure 5: NGS SSM Assembly block diagram during operations

During operation, the TCS provides the expected position of the NGS and the NCC uses the “global pointing model” to properly position the PWFS. The TCS accounts from image and pupil shifts due to the ADC correction in the PWFS. Image shifts are incorporated into the expected GS position, whereas pupil shifts are fed in the “differential offset model”, so that proper registration can be achieved even when the ADC shifts the pupil.

While the AO loop is closed, the NRTC computes the position of the pupil image and compares it the its expected position. Any discrepancy (“pupil error”) is reported to the TCS, which tries to correct this error by repointing the telescope. At the same time, the NRTC computes persistent tip-tilt-focus (TTF) errors in the PWFS measurements. These arise when the PWFS does not agree with the tier 1 OIWFS. These TTF errors are fed to the “differential offset block” so that they can be cancelled by repositioning the SSM. A configurable gain vector ("g") is applied to the TTF and pupil errors to adjust the responsiveness of the system.

Not shown in Figure 5 is the new requirement to also extract the size of pupil image. This information is used to adjust the plate scale by changing the position of the probes for each of the 3 T/T NGSs [3].

Calibration mode

For calibration, the implementation of the SSM Assembly is slightly modified as shown in Figure 6.

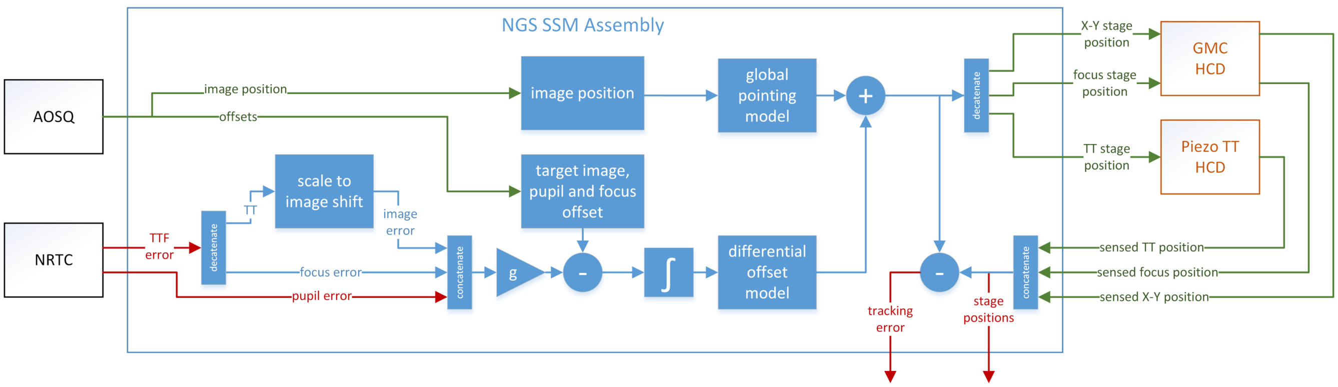

Figure 6: NGS SSM Assembly block diagram during calibrations

The TCS is not used. The AOESW (or the CalSW) provides the coordinates of the guide star. The NRTC feeds TTF error and pupil error to the "differential offset model". As the AO loop is closed on one of the calibration sources, the input of the integrator will be driven to 0, meaning that the position of the SSM mechanisms will be adjusted in order to cancel both the TTF error and the pupil error. The output of the integrator then provides the offsets required to the global pointing model. By analyzing these offsets for different GS positions, a more accurate global pointing model can be derived.

RTC implementation

The RTC estimates changes in pupil position. This is implemented by applying a matched filter to the normalized PWFS pupil image. The details of this process are described in reference [4]. During this calibration task, we derive the matched filter. Note that as commented before, we now need to estimate the size of the pupil in addition to its position. This will be accomplished by increasing the order of the matched filter so that these parameters can be estimated jointly.

TCS implementation

The TCS is responsible for translating the guide star position from sky coordinates (RA and DEC) to NFIRAOS focal plane coordinate.

Pointing models

Global Point Model

At this highest level, the SSM global pointing model is a function **P** relating the guide star position coordinates (x,y) in the FOV to the position of the five SSM motors (X_{ST}, Y_{ST}, X_{PUP}, Y_{PUP}, Z_{PUP}):

$(X_{ST}, Y_{ST}, X_{PUP}, Y_{PUP}, Z_{PUP}) = \mathbf{P}(x,y)$

The pointing model **P** is further broken down into two components:

$$\mathbf{P}(x,y) = \mathbf{P}_0(x,y) + \mathbf{P}_d(x,y)$$

$\mathbf{P}_0$ is the nominal pointing model, which can be built from first principles and parameters obtained from Zemax. Since the PWFS optical design is telecentric, $\mathbf{P}_0$ is quite straightforward: it simply sets X_{ST} and Y_{ST} to x and y, and sets Z_{PUP} to correct for defocus due to field curvature.

$\mathbf{P}_d$ is a field dependent perturbation model that accounts for the as-built system, including run-out of mechanism, effects of the cable chain, etc.

Our baseline is to model $\mathbf{P}_d$ as a 9x9 distortion matrix, which provides field dependent correction to the nominal pointing model, with the following form:

$\Delta(X_{ST}, Y_{ST}, X_{PUP}, Y_{PUP}, Z_{PUP}) = \mathbf{P}_d \# (1,x,x^2,y,yx,yx^2,y^2,y^2x, y^2x^2)^T$

Where # is the matrix-vector multiply operator.
This is a second order distortion model. The model order could be increased if needed. Increasing the model order will obviously increase the size of matrix $\mathbf{P}_d$.

Differential Offset Model
The Differential Offset Model **D** provides image position and pupil position adjustment:
$(\Delta X_{ST}, \Delta Y_{ST}, \Delta Z_{PUPM}, \Delta X_{PUPM}, \Delta Y_{PUPM}) = \mathbf{D}\ (\Delta X_{IM}, \Delta Y_{IM}, \Delta Z_{IM}, \Delta X_{PUP}, \Delta Y_{PUP})$
where $(\Delta X_{IM}, \Delta Y_{IM}, \Delta Z_{IM})$ are the required image position adjustments, and $(\Delta X_{PUP}, \Delta Y_{PUP})$ are the required pupil position adjustments.
Just like $\mathbf{P}_0$, **D** can be computed from Zemax based on the PWFS prescription:

- An image motion $(\Delta X_{IM}, \Delta Y_{IM}, \Delta Z_{IM})$ with no pupil motion $(\Delta X_{PUP}=0, \Delta Y_{PUP}=0)$ is achieved by moving the X and Y stages accordingly $(\Delta X_{ST}=\Delta X_{IM}, \Delta Y_{ST}=\Delta Y_{IM})$ and adjusting the focus accordingly by moving ΔZ_{PUPM}. Since the design is telecentric, the pupil position does not need to be readjusted $(\Delta X_{PUPM}=0, \Delta Y_{PUPM}=0)$.
- A pupil motion $(\Delta X_{PUP}, \Delta Y_{PUP})$ with no image motion $(\Delta X_{IM}=0\ \Delta Y_{IM}=0, \Delta Z_{IM}=0)$ is achieved by moving the pupil steering mirror in X and Y. However, since the pupil pointing mirror is not exactly in the focal, a counter motion of the X and Y stages is required in order not to move the image. The exact "lever arm" of the pupil steering mirror on image motion has to be calibrated.

Since **D** is a differential model, it does not depend on the position of the guide star as long as the adjustments are small.

Calibration procedure
Step 0: Initialization
The initial global pointing model and differential offset model built from Zemax are uploaded into the NCC.

Step 1: Zero-point calibration of the global pointing model
The goal of this calibration is to provide a zero-point to the global pointing model so that an on-axis guide star can be acquired with no image position error.
The FPM is deployed and the image position is set to "on-axis".
The PWFS is initialized with no binning and with the largest modulation available (10 λ/D). The largest modulation is used in order to minimize the diffraction effects and obtain the smoothest possible pupil images. This process is also helped by using the FPM instead of the NSS, since the FPM sources are slightly resolved (25 um in diameter), thus increasing the apparent modulation.
The NGS SSM Assembly is configured in calibration mode, with a 0 gain for pupil error and a small gain (~ 0.1) for image error (T/T/F). The DMs are flattened and the TTS is set to its zero position.
The NRTC is configured in NGS mode with a zero loop gain so that no DM/TTS correction is applied when the loop is closed. No NCPA slope offsets are applied. The AO loop is activated, which has the effect of getting the SSM mechanism to correct for any image position error. When the loop has converged after a few second, we open the AO loop and apply the current output of the differential offset model (T/T/F) as an offset to the global pointing model.
We should now be able to verify that when the TTS is at its zero position, and the global pointing model is used to acquire an on-axis star with no differential offset, no tip-tilt error is measured. If not, this calibration step must be repeated.

Step 2: Differential offset model calibration and verification
As discussed earlier, the lever arm (and possible clocking) between the spot motion induced by the pupil steering mirror and that induced by the X and Y stages must be calibrated.
This is done in a similar way as the previous step with the SSM assembly configured in calibration mode, with a 0 gain for pupil error and a small gain (~ 0.1) for image error (T/T/F).
This time, we move the pupil steering mirror in X and record the position of the X and Y stage when the loop has converged. We repeat this process with now moving the pupil steering mirror in Y. We are then able to update the matrix **D**.
The updated matrix **D** is tested as follows:

- Request a pupil offset of 10% of a sub-aperture, close the loop with the SSM Assembly in calibration mode, verify that the position offsets are zero, which means that the spot has not been moved
- Poke a sparse actuator pattern on DM0, and take a PWFS measurements with and without pupil offset. For each measurement, the position of each actuator can be estimated by computing the intersection of the four largest slope vectors in the area of the actuator, as illustrated in Figure 7.

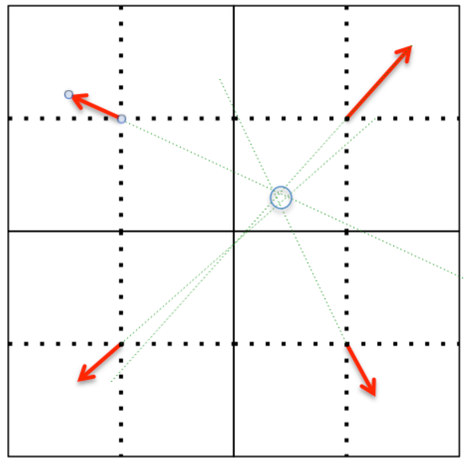

Figure 7: Method to locate the position of an actuator based on slope measurements. The estimated location is a the intersection of the green dotted lines (blue circle), which are aligned with the slope vectors.

Step 3: Computation of the pupil shift matched filter

With our Differential Offset Model validated, we can now move the pupil position by a known amount. We use this capability to build our pupil shift matched filter.

With the on-axis focal plane source exactly at the tip of the pyramid, we record the pupil image. The pupil image is obtained by extracting the four PWFS pupil images, registering them, and summing them (see section XXX).

We then use the SSM assembly to shift the pupil image by a small amount (~1% of an actuator pitch) in +X, -X, +Y and –Y, and for each shift, we record the new pupil image. The five images are used to compute the matched filter that we will use to measure pupil shift, as described in reference [4]. As noted before, the matched filter will need to be modified to provide an estimation of the pupil size. Since we cannot induce a change in pupil size from our calibration system, we will need to be an analytical modification.

Once the pupil shift matched filter is computed, we can implement it in the RTC, so that now the SSM assembly can offload pupil position as well as image position.

Step 4: Global Pointing Model Calibration

The global pointing model is tested at various points in the FOV. Initially, we start with a limited number of sources (maybe 25) across the field of view. For each source, we test the model by acquiring the source and then closing the loop with no AO correction using the SSM assembly in calibration mode. After the loop has converged, the output of the differential offset model will provide the residual pointing error for that particular point in the FOV. Once the residuals for all the points have been measured, a least square fit is performed to find the optimal distortion matrix $\mathbf{P}_d$. The process is iterated until the requirements from beginning of section 3.1 are met. If the residuals cannot be reduced after two consecutive iteration and the requirements are still not met, then the order of the distortion matrix must be increased.

Once a global pointing model that meets the requirements on the limited number of sources is found, another run is started with many more points in the FOV in order to verify the validity of the global pointing model.

3.2 Optical distortions due to NFIRAOS and IRIS

To achieve the astrometric requirements for NFIRAOS + IRIS entails calibrating optical image distortions. To reduce these distortions the dual OAP-Relay design of NFIRAOS already helps. But the remaining design and fabrication errors, plus optical polishing errors need to be calibrated out, especially the higher spatial frequency distortions. The main tool is the focal plane mask (FPM) whose holes are built to 5 um position tolerance and pre-measured and known to within 2 um (see section 2.1). However, this is still not accurate enough by itself.

The FPM is on an accurate dithering stage. It will be moved to an array of 4x4 or 5x5 positions and IRIS images taken at each position. Then the data reduction algorithm will jointly estimate the actual pinhole positions, the dither displacements and the optical distortions. This procedure is detailed in reference [5].

The process does not include the windows (which are superpolished < 9 nm RMS) and the telescope optics, which will cause low order distortions to be accounted for by reference stars in the field.

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