NFIRAOS

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ABSTRACT

NFIRAOS is an MCAO system for the Thirty Meter Telescope, serving 3 client scientific instruments. It has 2 deformable mirrors, 6 laser wavefront sensors, and uses up to 3 low-order (tip/tilt and/or focus) IR wavefront sensors (OIWFS) on each instrument and up to 4 guide windows on the client's science detector to correct atmospheric turbulence, windshake, optical errors and plate scale distortion. NFIRAOS' Intel Xeon-based real time computer is approaching final design review. This facility Adaptive Optics system for the TMT is cooled to -30 C. NFIRAOS is under final design at NRC Herzberg in Victoria Canada, and at industrial partners in Canada.

Keywords: MCAO, TMT, Thirty Meter Telescope, instrumentation, NFIRAOS

1. INTRODUCTION

NFIRAOS resides on the Nasmyth platform of TMT. NFIRAOS' unique design feature is that its optics are cooled to -30 C, resulting in 2.5x gain in efficiency for spectrographic observations between the OH lines in K band. The optics are mounted on a space frame structure 'optical table' enclosed by an insulated cold room thermal enclosure 8x10x4 meter, and the table and enclosure in turn are surrounded and supported by a steel exoskeleton. This steel frame, the Instrument Support Tower (IST), provides a direct load path to the TMT telescope Nasmyth platform for NFIRAOS and its three client instruments, which together have a total mass of 49 tonnes.

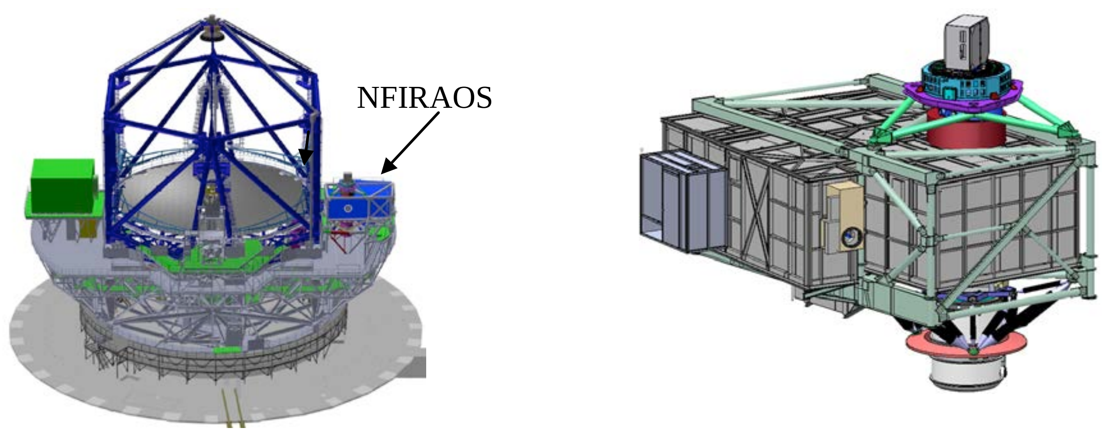

Figure 1 Left: TMT & NFIRAOS; Right: NFIRAOS with client instruments on top and bottom ports

Two client instruments are visible above and below NFIRAOS in Figure 1, attached to the IST by their own rotators and triangulated trusses. The thermal enclosure lies inside the IST, and has its own light weight aluminum exterior structure, composed mostly of square grid framework. There is a third instrument port on the side of NFIRAOS, which can be seen, unused, in the left image. The right image is from a viewpoint looking outwards from the primary mirror of the telescope towards the Nasmyth platform. The light from the telescope enters NFIRAOS' window on the left front in the right hand picture. To the left rear we can see a temporary servicing vestibule that permits personnel access to NFIRAOS, while keeping out dirt, and which will be removed in operation to reduce mass and wind cross-section.

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2. TECHNICAL REQUIREMENTS OF NFIRAOS

Table 1 summarizes the key specifications for NFIRAOS that flow from the science goals for wide field precision astrometry and photometry with high sky coverage, good image quality, low background and very efficient usage of telescope time. These in turn demand that NFIRAOS optical design have very low (<0.05%) distortion, few surfaces, high efficiency coatings, good internal calibration sources, and to be able to quickly switch among three client instruments.

Table 1 Fundamental and Derived Requirements of NFIRAOS

Requirements	**Derived AO design requirements**
High sky coverage (50% at the galactic pole)	• Laser guide star (LGS) AO • Natural guide stars (NGS) in NIR to sense tip/tilt/focus/plate-scale
Multi-conjugate AO with 2 DMs to sharpen guide star images over a large field of view	
Diffraction limited performance in J, H, and K bands (187nm/203nm RMS on-axis /30" dia.)	• 6 LGS and tomographic reconstruction • High spatial (60x60) and temporal (800 Hz) sampling • AO telemetry and PSF reconstruction • Distortion-free optical design
Astrometry (50 µarc-sec 30" FoV H band 100 s)	
Photometry (2% , 30" FoV λ=1µm 10 minutes)	
High optical throughput (80% over 0.8-2.5 µm with goal of 90% over 0.6-2.5 µm)	Cooled (-30°C) AO system with minimal number of optical surfaces.
Low background emission (15% of sky + telescope)	
Science ports (3 ports, f/15 with a 2' FoV)	2 instruments at first light

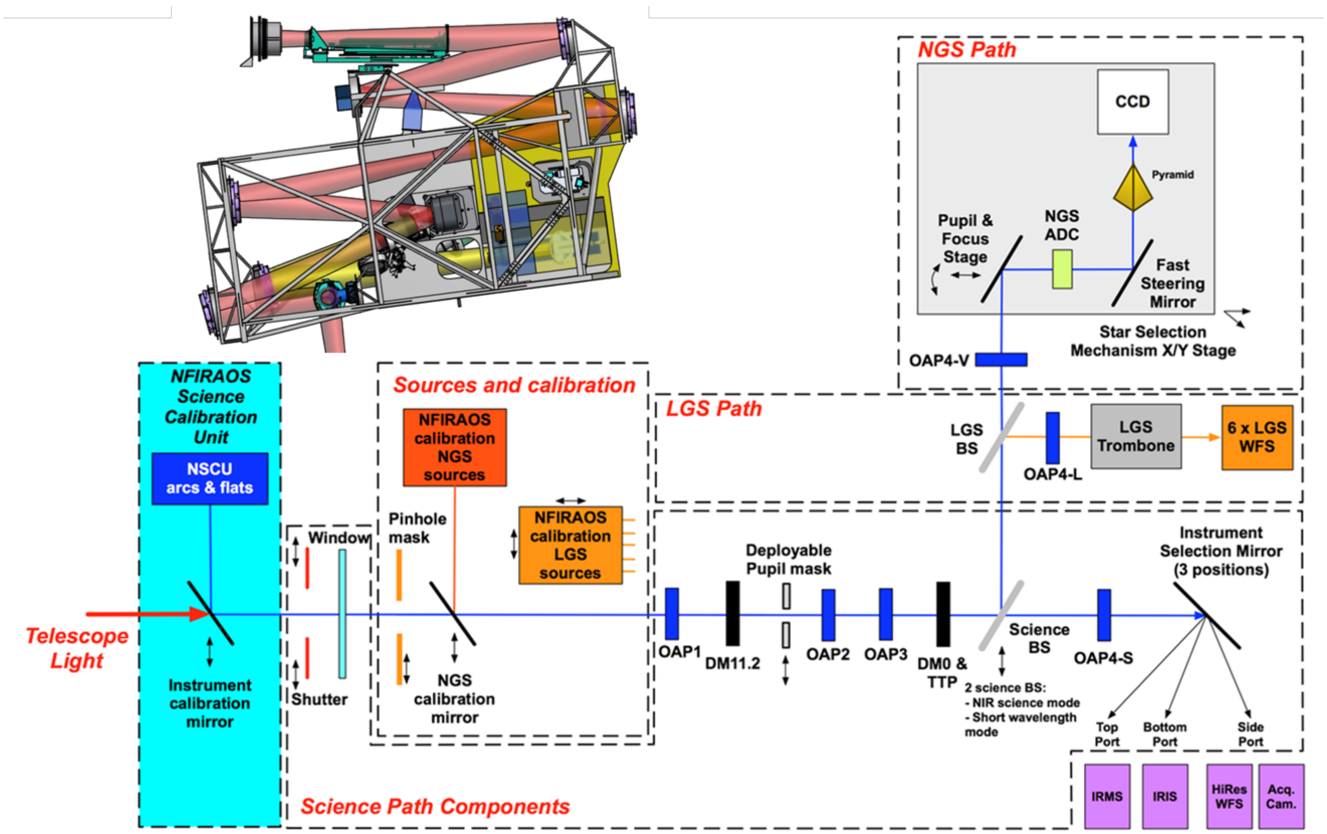

Figure 2 Block Diagram of NFIRAOS Optics; Inset: Overhead Plan view - Light path is top to bottom.

3. OPTICAL PATH BLOCK DIAGRAM

In Figure 2 we depict the optical paths throughout NFIRAOS. The main science path is the horizontal blue line running from left to right across the lower part of the figure. Light from the telescope comes from the lower left in this figure and first passes through an external calibration source for the instruments. This NFIRAOS Science Calibration Unit (NSCU), managed by the University of Toronto and built by industrial partners, contains an integrating sphere with flat field and wavelength standards (arcs). The NSCU has an input shutter, to permit daytime usage and to keep out dust when not observing and a deployment mechanism, which is normally parked out of the way to allow telescope light to pass into NFIRAOS.

Light then passes through NFIRAOS' own entrance shutter and through the window into the cold enclosure, and arrives at the telescope's own focus. At this focal plane, mechanisms insert two different calibration devices. One is a pinhole mask which is illuminated by the NSCU. Alternatively NFIRAOS may deploy into the focal plane, a plate with 17 fibre-fed adjustable brightness sources arranged throughout the 2 arcminute field of view. Then downstream from focus there is an LGS simulator with 6 fibre sources carried on very thin spiders.

The science path is composed of two off-axis-paraboloid (OAP) relays in series, each with a deformable mirror, one of which (DM11) is conjugate to 11.6 km, while the other (DM0) is conjugate to the ground (DM0) and carried on a tip-tilt stage (TTS). The near-IR light is transmitted through the science beamsplitter and reimaged by the last conic mirror (OAP-S). On the way to focus the bean is diverted up, down or sideways to the client instruments by the instrument selection mirror (ISM). During early operations, one of these clients will be a surrogate device with and acquisition camera and a high resolution WFS (HRWFS) for calibration and diagnostics

Guide star light reflects off the science beamsplitter, (upwards in this figure) and immediately the laser light is reflected out to the LGS WFS path, where it is reimaged by OAP4-L a copy of the fourth science paraboloid. A trombone compensates for changing range distance to the sodium layer and then the light is reaches 6 Shack-Hartmann WFSs. Natural guide star visible (600 – 800 nm) light passes through the LGS beamsplitter, and is also reimaged by a 3rd copy with the same prescription (OAP-V), where it is measured by a pyramid WFS (PWFS) carried on an XY stage (star selection mechanism) that selects a single guide star from the field.

The CCD of the PWFS can be binned and read out at slow speed to serve as a 12x12 Truth WFS, or can be read unbinned (96x96) at full 800 Hz frame rate for NGS SCAO operation.

4. OPTO-MECHANICAL LAYOUT

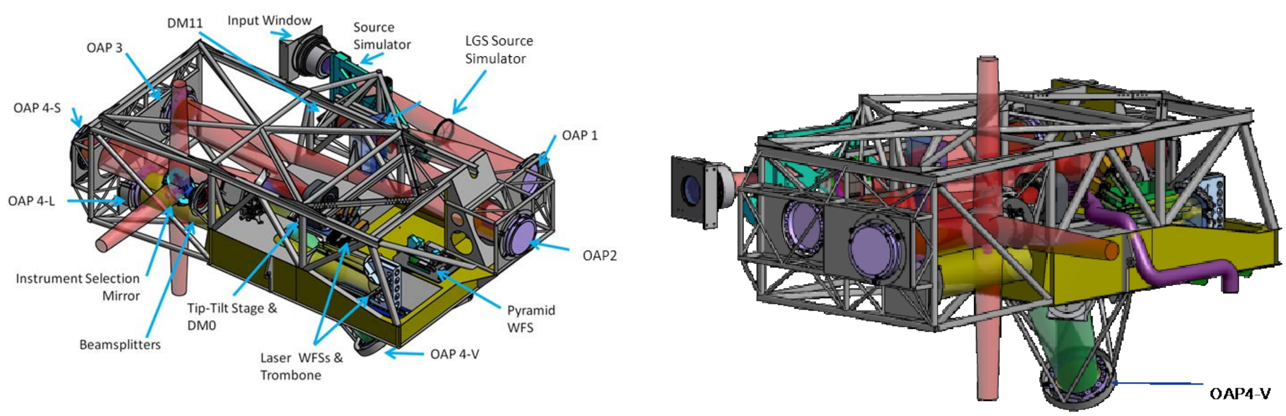

Figure 3 Opto-mechanical table (space frame)

In Figure 3 the entire science path beam is shown in red and lies entirely in a horizontal plane, until it reaches the instrument selection mirror where it is then directed to the science ports on the top, bottom and side of NFIRAOS. The input window admitting telescope light is top-centre in the figure, followed by the source simulator with the pinhole mask and fibre sources, and then the spider with the LGS fibre sources, before reaching the first OAP1 on the right. Each OAP is on a flexure mount with tip/tilt adjustment. DM11, conjugate to 11.6 km is located within the first OAP relay, formed by OAP1 and OAP2. The second relay, formed by OAP3 & OAP4, contains the tip/tilt stage carrying DM0. After reflection from DM0, the science light passes through the science beamsplitter to OAP4-S and back to the instrument selection mirror -- three exit beams are shown, with the ISM in its three positions.

The laser light is shown in yellow as it passes the trombone on the lower right, and then individual pickoff mirrors direct the six laser guide star into Shack-Hartmann WFSs. The natural guide star light is shown in green in the right half of Figure 3, descending after reflection from the science beamsplitter and transmitted through the LGS beamsplitter. This NGS beam, which has been collimated by OAP3, contains light with wavelengths from 600 to 800 nm and is reformatted into an f/15 beam by OAP4-V before it reaches the ISM.

5. SUBASSEMBLIES OF NFIRAOS

In this section we describe various components of NFIRAOS, beginning with the thermal enclosure and optical table.

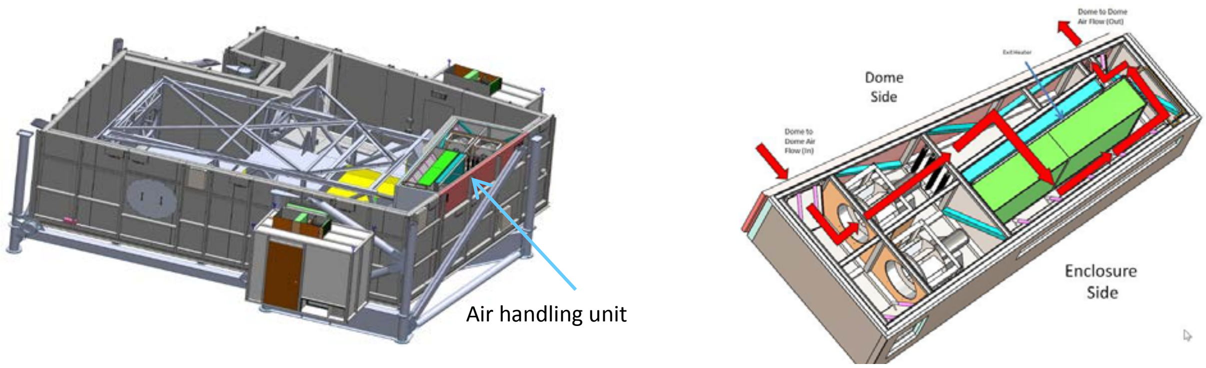

Figure 4 Left: Thermal Enclosure, and optical table (unpopulated); Right: Air handling unit - defrosting

5.1 Thermal Enclosure

The left image in Figure 4 shows the thermal enclosure with the top panels removed. Inside is the space-frame optical table without opto-mechanical subassemblies installed. Servicing vestibules are visible in the foreground, and behind NFIRAOS. On the left front in this picture is an insulated port plug which will be removed to install an instrument. There is a gate valve behind the port plug, permitting instrument exchange without warming NFIRAOS. The insulated enclosure walls are built from individual panels 150 mm thick, each with a buried cold plate approximately 1/4 of this distance from the inner surface. Each cold plate has an attached serpentine refrigeration channel, and the inlet mass flux is chosen to overfill a channel. That means some refrigerant ($C0_2$, also known as R-744) remains liquid at the exit at the bottom of each panel. This ensures a constant temperature across each panel, since there is always liquid to evapourate or vapour to condense if the heat leakage from the dome changes due to weather conditions. The panel temperature is controlled to -30 ± 0.5 C by regulating the suction pressure at the exit of the panel, and therefore stabilizing the evaporation temperature within the panel. These cold panels, consume ~3 kW of cooling power, and maintain the temperature while avoiding vibration typical of conventional refrigeration systems with fans. There are also heaters on the exterior surfaces to keep them isothermal with the dome air to avoid condensation and cold plumes.

However, for servicing, the panels would take nearly a week to reach dome or operating temperature, so there is a powerful 25 kW air handling unit detailed in the right image in Figure 4, which is responsible for daytime cooldown, warmup and humidity control.

5.2 Entrance Window

The left side of Figure 5 shows a cross-section of the entrance window assembly and its penetration through the thermal enclosure (section 5.1).

The enclosure wall is shown in blue, and its supporting frame is gray. The vacuum vessel is orange and the silica windows are dark blue, with the outer window on the right facing the dome air, and the inner window on the left facing the -30 C air inside NFIRAOS. The left hand section of the vacuum vessel, protruding inside NFIRAOS has refrigerant coils to maintain it at -30 C. Inside the vacuum vessel are two thermally-controlled baffle sections, to radiatively heat and cool the outside and inside windows respectively and maintain each within ±0.5 C of the temperature of the air they are exposed to. Without this control, the outer window would lose heat by radiation to the interior of NFIRAOS and possibly sub-cool below the dew point in the dome, causing condensation. As well, by maintaining a low temperature difference w.r.t. the dome and NFIRAOS air, the windows minimize self-induced turbulent "window seeing." The right

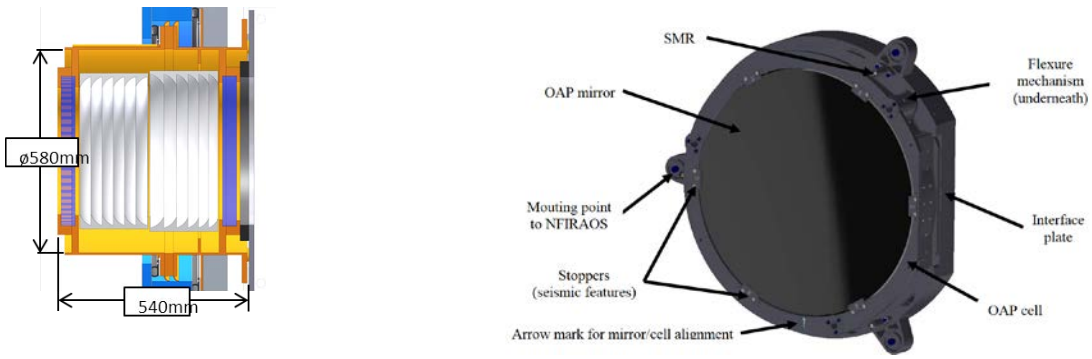

Figure 5 Left: Evacuated Double Pane Entrance Window; Right Mirror Cell

hand baffle is heated warmer than the dome, and the flat (right hand) surface of each baffle ring is highly emissive to warm the outer window and balance the heat loss to the interior of NFIRAOS. Meanwhile its curved surfaces are reflective (low emissivity) and act as Narcissus mirrors so that the opposite (further away) window sees itself in these reflective surfaces avoiding radiative heat exchange with these curved surfaces. The left hand baffle section, near to the inner window is thermo-electrically cooled to ~ -40 C, so that its emissive flat surfaces provide a cold load to balance the radiation from the outer window.

5.3 Source Simulator

Just inside the entrance window, there is a mechanism with several calibration sources. On the right side of the first

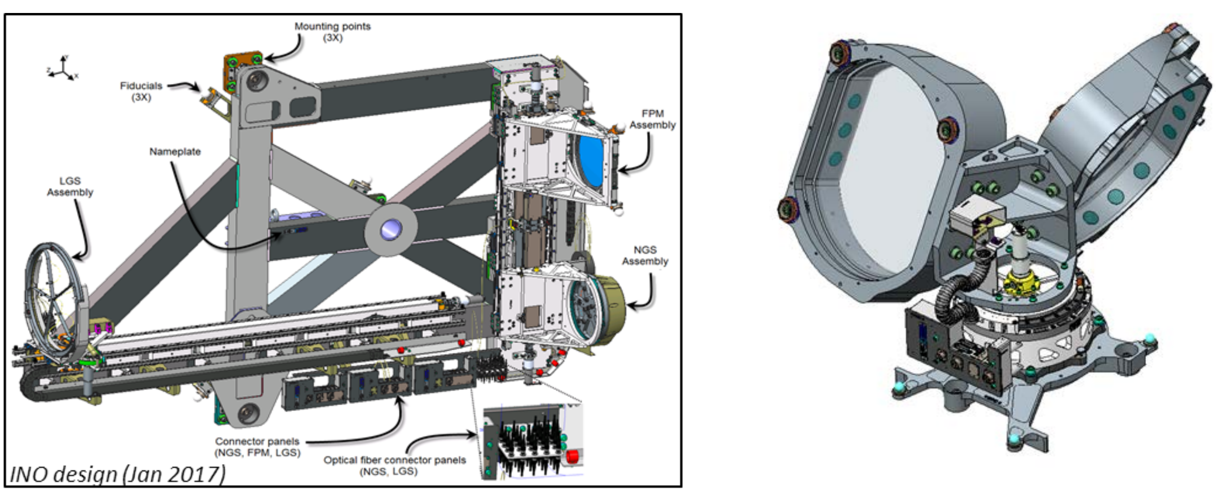

Figure 6 Left: Source Simulator; Right: Beamsplitter changing mechanism

picture in Figure 6, are a Focal Plane Mask (FPM) with a grid of pinholes, and a Natural Guide Star Assembly with up to

17 fibre-fed sources arranged in the 2 arcminute FoV, some representing seeing limited stars and some with smaller diffraction limited apertures. Some of these fibres are fed by a precision adjustable attenuator, to calibrate NGS WFS performance versus signal. On the left side of the first image in Figure 6 is a spider LGS source assembly, that flips into the beam and carries six fibre-fed sources with a wavelength of 589 nm. The LGS source spider moves axially along the beam to simulate changing range distance to the sodium layer.

The FPM and NGS assemblies are shown retracted just above and below the telescope input focal plane respectively. They run on the same stage rails, and move separately into the focal plane, with appropriate electrical interlocks to prevent collisions. The FPM is illuminated by the Science Calibration Unit (NSCU), an instrument wavelength and flat-field source, deployable in front of NFIRAOS' entrance window. The FPM has a central region with a dense grid of diffraction limited holes with 0.46 asec spacing (1 mm physical distance), over-filling the science image detector (whose planned size is 34 arcseconds square) of IRIS, the first light client instrument. This mask can be dithered by ±1.5 grid pitches in XY, to calibrate optical distortion to achieve the astrometry requirements. Outside this central region, a sparser grid of holes is available to calibrate pointing models for WFSs, and to fully illuminate DM11 for e.g. calibrating registration of WFSs to DM11.

5.4 OAP Mirror Cells for Alignment

Figure 5, right, shows a mirror cell for an OAP. It has two large components: the OAP cell with a mirror, and an interface plate. These two are joined by three flexure adjustment mechanisms for tip/tilt alignment. These flexure mechanisms act as repeatable bayonets, permitting the removal and accurate replacement of a mirror plus its cell onto the interface plates that will remain permanently affixed to the optical table.

5.5 Beamsplitters and Changer

The main science beamsplitter is in a collimated beam after DM0, and is a dichroic on a fused silica substrate that transmits light in the wavelength range from 800 to 2400 nm, and reflects light shortward of 800 nm. It has an anti-reflective coating on the downstream surface, and is slightly wedged to displace ghost images to just outside of the AO control radius ("dark hole" of the primary image of a point source). The beamsplitter is on a changer mechanism, shown in the right image of Figure 6. The second position of the changer contains an engineering beamsplitter, a partially-silvered 50/50 intensity splitter. Its main purpose is to permit visual alignment, described in Section 6 Optical Alignment Procedure, but it also assists the goal to do some astronomy in the 600 – 800 nm range.

The shorter wavelengths reflected from the front surface of the beamsplitter are immediately divided by a second, stationary, LGS beamsplitter that reflects the 589 laser light towards the LGS arm containing OAP4-L, and the trombone etc. Light passing through the LGS beamsplitter descends out of plane to OAP4-V, seen suspended below the optical table in Figure 3, and then is folded to reach the visible natural guide star wavefront sensor (NVNW).

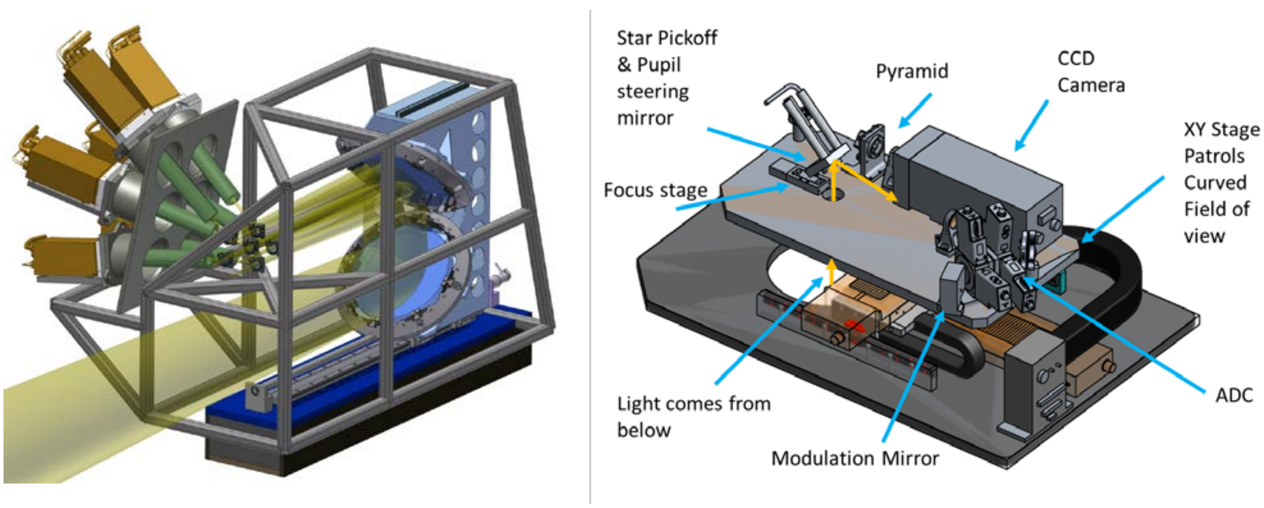

Figure 7 Wavefront sensor assemblies. Left Trombone & LGS. Right: NGS (NVNW)

5.6 LGS Wavefront Sensors

Laser light, after reimaging by OAP4-L, does a double reflection from a pair of trombone mirrors, on a stage with >800 mm of travel. This trombone (Figure 7, left) focuses the sodium layer onto the WFSs and is designed for range distances between 85 and 235 km. After the trombone, individual pickoff mirrors divert each laser guide star towards collimator lens barrels. Each barrel begins with an 8-arcsecond diameter field stop, and then re-images the pupil onto 30 mm diameter lenslet arrays. These lenslets are part of each camera assembly (VCAM), because of the tight tolerances needed (especially for clocking) between the lenslets and the CCD. This arrangement permits rapid repair of NFIRAOS by field-replacement of whole cameras, without re-aligning optics. The CCDs themselves are polar co-ordinate devices with compact islands of 0.8-arcsecond pixels aligned with the elongated laser spot images. The further outward on the pupil, the more elongated the spot, and so the CCD islands have 6x6 pixels behind lenslets near the centre, and 6x12 near the perimeter. This scheme reduces the number of pixels needed and optimizes the tradeoff between laser power, readout noise and frame rate.

5.7 Visible Natural (NGS) Wavefront sensor

The VNW is a pyramid wavefront sensor (PWFS) that has two main roles: 1) a truth WFS for laser guide star MCAO mode; and 2) a high speed, high order WFS for NGS (SCAO) operation. Also its signals can stand in for one of the three On-instrument wavefront sensors (OIWFS), if a suitable guide star is not available near the science field – since VNW is fed by a dichroic, it can operate arbitrarily close in the field to e.g., an Integral field unit, whereas OIWFS pickoff mirrors may sometimes vignette the scientifically interesting object.

Light from OAP4-V is folded to arrive at VNW traveling upwards. The pyramid WFS is carried by an XY stage that patrols the 265 mm diameter (120 arcsecond) technical field of view and selects a single star using a pickoff mirror near focus. Because the focal plane is curved, this 45 degree fold mirror compensates focus by travelling on a short linear stage parallel to the main X stage, The X axis travel of the main stage is compensated for this focus motion in the pointing model for the stages. Furthermore, the pickoff mirror is on a slow-speed piezo tip/tilt stage for fine control of pupil steering. Thus a total of five mechanical axes form the star selection mechanism (SSM) to select a star and deliver its image onto the tip of the pyramid while centring the four pupil images correctly onto the CCD. This detector is a more conventional rectangular pixel array, housed in a camera that is mechanically identical to the LGS CCDs, but without a lenslet array. It employs the same electronics as the LGS WFSs, but with fewer readout boards.

On the way to the pyramid, the light passes through an atmospheric dispersion compensator ADC) and reflects from a fast piezo Tip/tilt mirror that simultaneously modulates and dithers the beam. In NFIRAOS, modulation means making the beam travel in a circle (~ 5 /D diameter) around the tip of the pyramid exactly once per frame to extend the dynamic range of the measurements. Dithering is a slower speed (typically ¼ frame rate) low amplitude (~1% of modulation) circular waveform that the real time computer uses to assess optical gain of the PWFS.

Table 2 Component specifications

Deformable mirrors	63x63 and 76x76 actuators at 5 mm spacing 10 µm stroke at -30°C, ≤2% per time decade creep at -30°C
Tip/Tilt Stage	500 µrad stroke with 0.05 µrad angular resolution 80 Hz bandwidth
NGS WFS Detector	256x256 CCD, 96x96 virtual sub-apertures ~0.8 quantum efficiency, ~1 electron at 100 Hz frame rate
LGS WFS Detectors	60x60 sub-apertures with 6x6 to 6x15 pixels each ~0.9 quantum efficiency, 3 electrons at 800 Hz

Low-order IR NGS On-Instrument WFS detectors	1024x1024 pixels (sub-array readout on ~8x8 windows) ~0.6 quantum efficiency, 3 electrons at 10-200 Hz
Real Time Computer	Matrix Vector Multiply 35k x 8k at 800 Hz

6. OPTICAL ALIGNMENT PROCEDURE

The integration plan for NFIRAOS begins by using a metrology bench to measure all OAPs mounted in their cells and interface plates, to determine the as-polished focal length, and the off-axis distance to the vertex in a local coordinate system defined by Spherical Magnetic Retroreflectors (SMR), which are permanently part of each interface plate. We will also apply a fiducial mark on each OAP indicating where we would like the chief ray to hit the mirror. Then using Zemax, we will re-optimize the planned locations of each OAP. First we will install the interface plates separately and will survey them into position in XYZ and clocking, using optical coordinate measuring machines to locate the SMRs within 50 μm, and then install the OAPs by inserting the cell and flexures into the interface plates. The optical axis will be established by the line joining the central hole in the focal plane mask, (section 5.3) and the fiducial mark on OAP1. With an alignment telescope, will look into the front window of NFIRAOS and boresight the telescope to these two features. Then we will re-focus the telescope onto the surface of OAP2, and using the flexure adjusters on OAP1, tip and tilt OAP1 until we can view the OAP2 fiducial mark on axis. Then we will refocus the telescope onto the next optic (OAP3), and tip and tilt OAP2 until the next fiducial is in line, and repeat the procedure to the end. Finally, with a patrolling WFS in test equipment on an instrument port, we will measure the output image position and pupil location and translate and shim NFIRAOS' instrument locating pins so that an instrument can bolt on and be well-aligned with the beam. This test instrument NSEN also contains a 20 arcsecond FoV imager that will serve as an acquisition camera during early operations.

7. REAL TIME COMPUTER

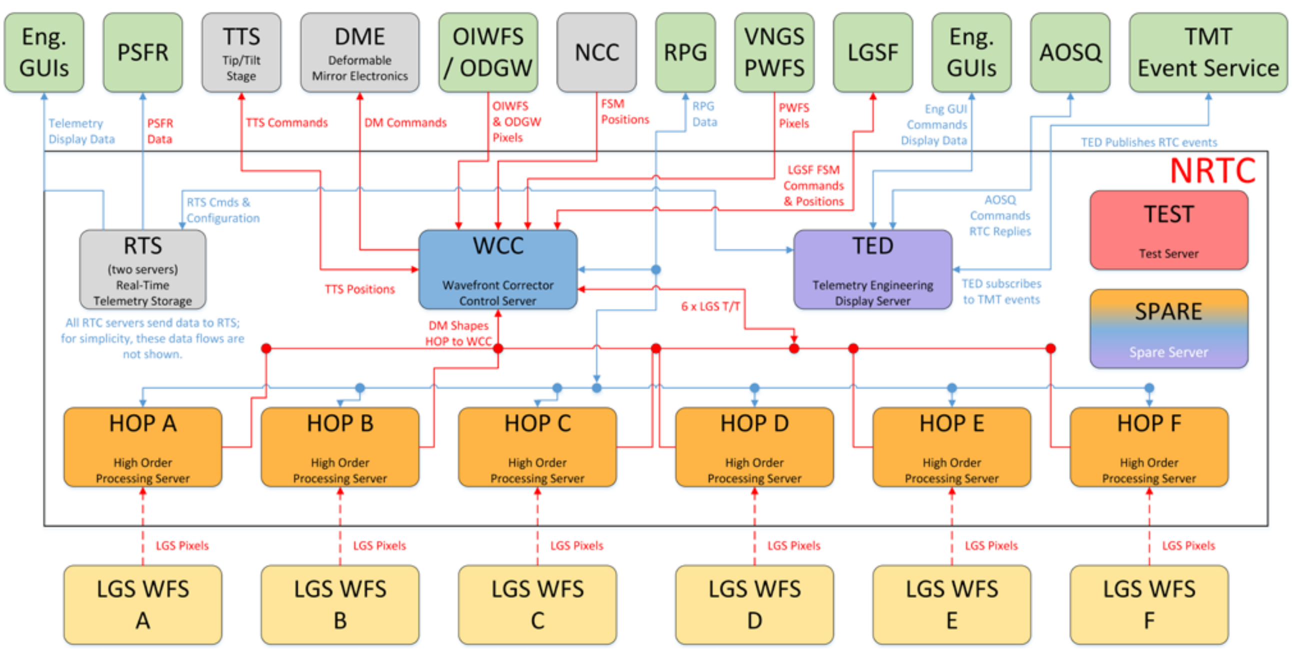

Figure 8 Real Time Computer

NFIRAOS RTC uses Intel Xeon servers, and does a matrix-vector multiplication on the WFS gradients to calculate DM actuator errors. In Figure 8 the main data flow is from bottom to top. Each LGS WFS sends its pixels to its own private high-order processor (HOP) with four 20-core CPUs, one CPU per quadrant of the CCD. These CPUs calculate gradients from each subaperture spot using a matched filter and then process a stripe of columns of the control matrix, with individual cores doing a piece of the stripe. One CPU in a HOP server adds the four partial DM error vectors and forwards them to the wavefront control computer within (WCC) that combines these as an input to the main control integrator. The WCC also processes pixels from: the truth WFS to correct errors from interaction of the sodium layer with the LGS WFS; plus (typically) three On-Instrument WFSs measuring high-speed Tip/Tilt/Focus to control these three modes, plus plate scale; as well as low-data rate pixels from on-detector guide windows ODGW on the science detectors, which are the long term references for flexure and rotator stability.

Data is archived on a pair of Real-time Telemetry Storage (RTS) servers, for diagnostics, but mainly for Point Spread Function Reconstruction. This PSFR data will be overwritten each night by new data, and the calculated point spread functions will go into the science repository associated with each exposure. Other servers create user interface GUIs and can stream test data through the RTC. Separate from the RTC there is another computer provided by TMT, the reconstructor parameters generator RPG, a farm of GPUs that will take RTC telemetry data and return a new control matrix to the RTC every 10 seconds.

The RTC resides in the TMT computer room, and has private Ethernet fibres through the telescope cable wrap directly to the RTC's own switch in the NFIRAOS electronics cabinet in red below NFIRAOS' enclosure in Figure 9. These fibres convey pixels to the computer room and return DM and TTS commands to the NFIRAOS Nasmyth electronics cabinets that contain high-voltage DM amplifiers, and also motor controllers, refrigeration controllers and light sources for the Source Simulator.

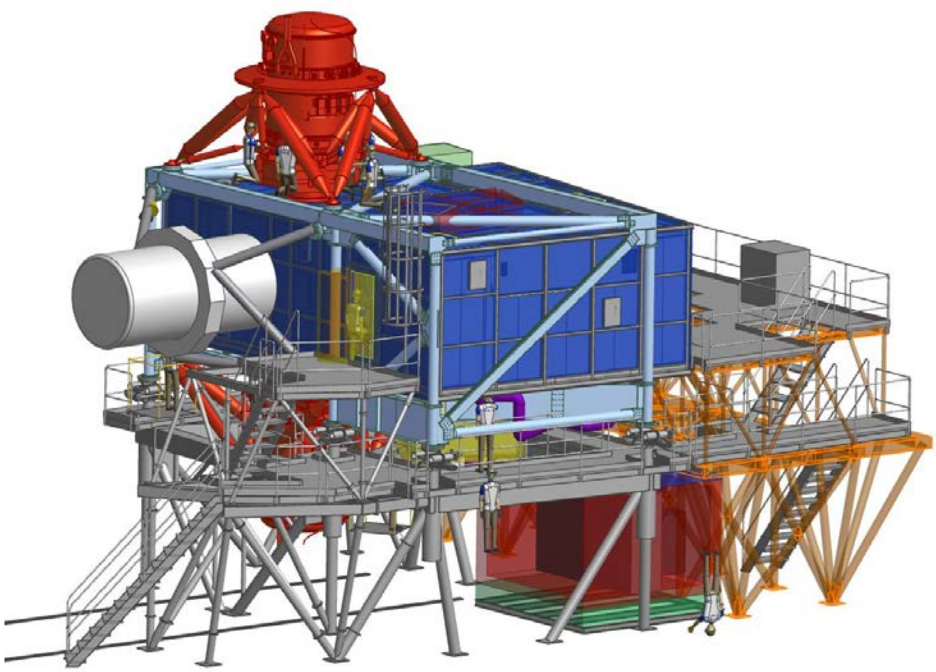

Figure 9 NFIRAOS on Nasmyth platform

8. CONCLUSION

NFIRAOS for the Thirty Meter Telescope is well advanced towards its final design review in mid-2018. It is a multi-conjugate adaptive optics system with two deformable mirrors and six 60x60 LGS WFS, whose real time computer also makes use of inputs from up to three on-instrument WFSs in each of three client instruments observing in the near infra-red from 800 to 2400 nm. To reduce background emission, NFIRAOS is cooled to -30 degrees with a tight tolerance (±0.5 C) and incorporates sophisticated humidity and temperature control including an evacuated entrance window.