The Final Design of NFIRAOS

David R. Andersen*[a], Glen Herriot[a], Jenny Atwood[a], Peter Byrnes[a], Jeff Crane[a], Adam Densmore[a], Jennifer Dunn[a], Joeleff Fitzsimmons[a], Tim Hardy[a], Kate Jackson[a], Dan Kerley[a], Olivier Lardière[a], Coba Ricard[a], Malcolm Smith[a], Jonathan Stocks[a], Jean-Pierre Véran[a], Corinne Boyer[b], Luc Gilles[b], Gelys Trancho[b], Lianqi Wang[b]

[a]NRC Herzberg Astronomy and Astrophysics, 5071 W. Saanich Rd., Victoria, BC, V9E2E7, Canada; [b]Thirty Meter Telescope Observatory Corporation, Pasadena, California 90807, USA

ABSTRACT

The Narrow Field Infrared Adaptive Optics System (NFIRAOS) is the first-light facility Multi-Conjugate Adaptive Optics (MCAO) system for the Thirty Meter Telescope (TMT). The National Research Council Canada (NRC) Herzberg Astronomy and Astrophysics (HAA) Research Centre and our industrial subcontractors are developing NFIRAOS and its real-time controller, while TMT is responsible for the laser guide-star facility, the adaptive-optics (AO) executive software, the wavefront-sensor detectors, readout electronics, and the deformable mirrors. NRC HAA successfully presented the design of NFIRAOS at a final design review in June 2018.

NFIRAOS itself will provide diffraction-limited performance in the J, H, and K band over a 34 arcsec diameter field with 50% sky coverage at the Galactic Pole. Years of effort have been spent to ensure that TMT and NFIRAOS deliver images that on average will be the sharpest of any existing facility AO system. Sky coverage is also a key performance metric. For astronomers to be fully satisfied with TMT + NFIRAOS, they must be able to observe their key science programs. The laser guide stars, the use of MCAO, and the on-instrument near-infrared tip/tilt/focus sensors (OIWFSs) all contribute to achieving diffraction-limited performance 50% of the time at the North Galactic Pole. Here, we present the final design of NFIRAOS and its subsystems and highlight some of the important performance budgets and design solutions made along the way.

Keywords: Multi-Conjugate Adaptive Optics, Adaptive Optics Error Budgets, Astrometry

1 INTRODUCTION

NFIRAOS is an ambitious MCAO system that will be ready by first light of TMT (Figure 1)[1,2]. After the Canadian government awarded money to TMT in 2015, NRC HAA subdivided NFIRAOS into subsystems and subcontracted the final design of these subsystems to Canadian industry. The project has now engaged six Canadian industrial partners to develop the final design of eight major NFIRAOS subsystems. Working with industry to develop designs to specifications was a new approach for the NRC team, and NFIRAOS has benefited greatly from these companies' expertise.

NFIRAOS itself will provide diffraction-limited performance in the J, H, and K bands (enabling science at wavelengths between 0.8 and 2.4 μm over 34 arcsec diameter fields with 50% sky coverage at the Galactic Pole. By virtue of its size and the excellent AO correction courtesy of NFIRAOS, TMT will yield extraordinarily high spatial resolution in the near-infrared (e.g. Figure 2). Years of effort have been spent to ensure that TMT and NFIRAOS deliver images that on average will be the sharpest of any existing facility AO system; NFIRAOS is required to deliver Strehl ratios of greater than 50% in H-band in median conditions[1,3]. Sky coverage is, of course, also a key performance metric. For astronomers to be fully satisfied with TMT working with NFIRAOS and its client instrument, the InfraRed Imaging Spectrograph (IRIS)[4], they must be able to observe their key science programs. Six laser guide stars (LGS), the use of MCAO, and the on-instrument near-infrared tip/tilt/focus sensors (OIWFSs) to guide on Natural Guide Stars (NGS) all contribute to achieving diffraction-limited performance 50% of the time at the North Galactic Pole[5,6]. This sky coverage fraction increases dramatically for fields closer to the galactic plane where many more stars are available.

*David.Andersen@nrc-cnrc.gc.ca; phone 1 (250) 363-8708

Figure 1: NFIRAOS (in blue) as it would appear from the TMT Nasmyth platform. The client instrument IRIS (grey) is shown below NFIRAOS. The NFIRAOS electronics enclosure is shown in green.

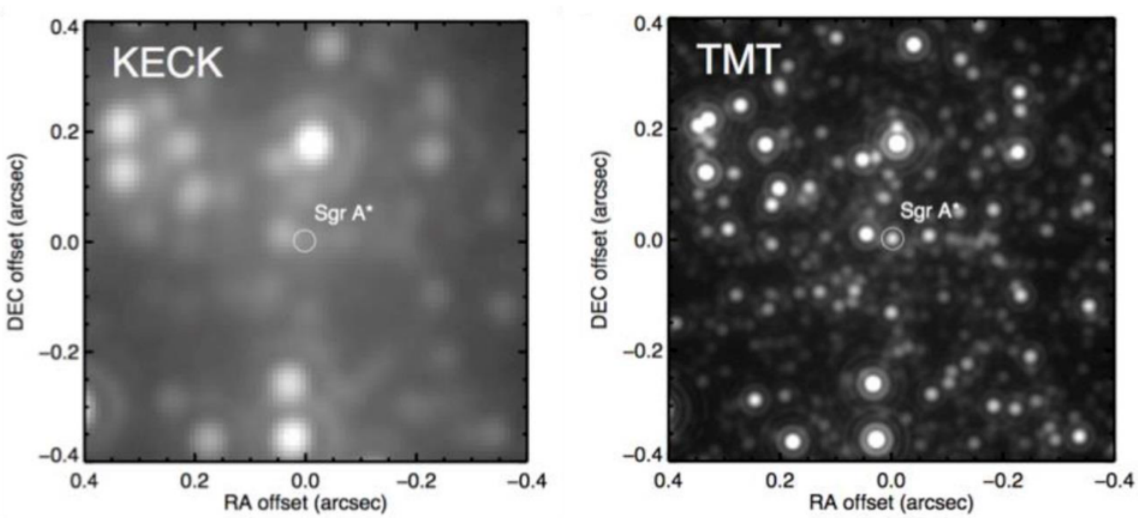

Figure 2: Comparison of diffraction-limited images taken with Keck Observatory AO versus the expected performance of NFIRAOS and IRIS. This simulation shows the center of our Milky Way galaxy. A 4 million solar mass black hole resides at the location of the radio source Sagittarius A*. By monitoring stars orbiting around the black hole, TMT astronomers will be able to test the predictions of General Relativity. (Credit: T. Do, IRIS science team)

The NFIRAOS functionality and performance has been captured in roughly 400 detailed requirements that have been driven by numerous performance budgets and studies. Many of the NFIRAOS design decisions were made to maximize point source sensitivity. A few examples of these design choices include: cooling NFIRAOS to -30° C to minimize the thermal background[7] and to set tight limits on the pupil alignment budget (undersizing the cold Lyot stop in IRIS throws light away and broadens the diffraction pattern). The TMT and NFIRAOS and IRIS teams have also invested in understanding and minimizing photometric and astrometric errors[8]. One major implication of these studies was that it was recognized that astrometry would be compromised in the presence of a rotating distortion field. The NFIRAOS optical relay was redesigned using four off-axis parabolas (OAPs) to minimize both wavefront error and distortion from NFIRAOS thus enabling 50 μas precision astrometry for H<20 stars in less than 100 seconds (with a noise floor of 10μs). Another area of great focus for TMT in general, and NFIRAOS and IRIS in particular, is understanding and minimizing observing overheads. The complete target acquisition, involving the slewing of the telescope, propagation of the laser guide stars, closing the AO loops, and confirmation of the target field, is required to be completed in less than 5 minutes.

Table 1: NFIRAOS Driving Requirements

Requirements	Derived AO design requirements
High sky coverage (50% probability of meeting performance specifications at the Galactic Pole)	Laser guide star (LGS) adaptive optics Three OIWFS to sense tip-tilt/focus/plate-scale with NGSs in near-infrared Sharpened NGS over a large 2′ field of view
Diffraction limited performance in J, H, and K bands (187nm/203nm RMS wavefront error on axis/34″diameter in median conditions)	Multi-conjugate AO with two deformable mirrors for a large corrected field of view Six LGSs with tomographic reconstruction High spatial (60 × 60) and temporal (800 Hz) sampling
Astrometry (50μarc-sec over 30″ in H band, 100s exposure) Photometry (2% over 30″ at λ= 1 μm in 10 minutes)	AO telemetry and point-spread function reconstruction Distortion-free optical design
High optical throughput (80% over 0.8–2.4 μm) Low background emission (<15% of background from sky and telescope)	AO system (cooled to –30°C) with a minimal number of optical surfaces High-efficiency coatings
Science ports (3 ports, f/15 with a 2′ FoV)	Instrument selection mirror; Common interface at 3 ports
High efficiency and availability	Downtime < 0.4% Highly automated observing via observatory sequencers Capacity to resume in < 6 hrs from 200-year earthquake Large optics survive 1000-year earthquake

In these proceedings, we provide a summary of the NFIRAOS design in the follow section followed by a discussion of some selected performance budgets in section 3. In the conclusion, we summarize our design approach and give an indicate what the next steps in the fabrication of NFIRAOS will be.

2 DESIGN

A large fraction of NFIRAOS was designed by industry under the supervision of NRC HAA. NRC issued subcontracts for eight subsystems to six Canadian firms: Accent Refrigeration Systems; ABB Bomem; Dynamic Structures; Institut national d'optique – INO; Quantum Technology; Sightline Engineering. NRC HAA managed the subcontracts and defined the requirements and interfaces of individual subsystems. The industry partners successfully designed these subsystems to requirement, and will fabricate, assemble and test the individual subsystems before shipping them to Victoria for integration at NRC HAA. In this section, we put NFIRAOS in context within the observatory, and then describe the opto-mechanical and software design of the instrument.

NFIRAOS will be mounted on the –X Nasmyth platform of the telescope. In Figure 1, the medium-blue box is the thermal enclosure; the light-blue frame is the Instrument Support Tower (IST) that carries NFIRAOS, three client instruments, plus the NSCU. The moving telescope elevation journal is not shown in the figure, but would be just to the left of NFIRAOS with the primary mirror to the left of that. The telescope provides the structure (in gold) that holds NFIRAOS above the Nasmyth platform. This structure also includes stairways for three access points: at the roof, via

NFIRAOS personnel entrances at mid-level, and adjusters on the lowest level. The adjusters (in red) are provided by the telescope structure and form the main mechanical interface to the telescope.

The Infrared Imaging Spectrograph (IRIS), the first-light instrument, is shown (in grey) suspended below NFIRAOS. The NFIRAOS Sensor (NSEN, a test wavefront sensor plus acquisition and diffraction-limited cameras) is shown mounted on the side instrument port of NFIRAOS. Out of sight beyond the far-left corner of NFIRAOS is the NSCU that feeds wavelength and flat-field calibration light through NFIRAOS.

3.3 Opto-Mechanical Design Overview

Telescope light (see Figure 3 and **Error! Reference source not found.**, starting from the left) first passes through the input shutter of the NSCU, then past the deployable alignment telescope between the front of NFIRAOS and the NSCU. Light enters the ENCL through the NFIRAOS entrance window.

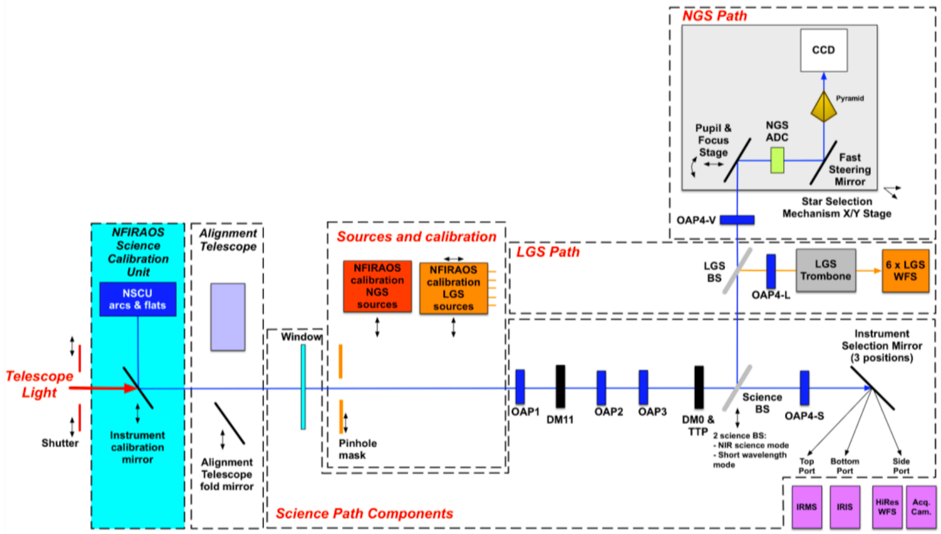

Figure 3: NFIRAOS block diagram.

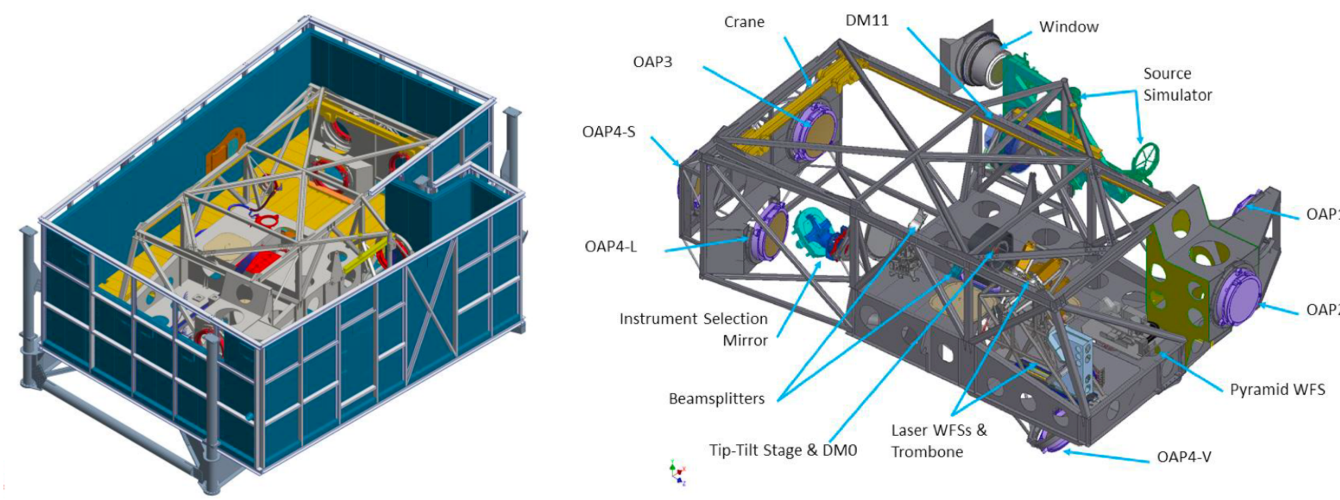

Figure 4: Left Panel – The NFIRAOS optical table (TABL; light grey) mounted on the Instrument Support Tower (IST; dark grey) inside the optical enclosure (ENCL; blue). The roof of the ENCL and top members of IST are not shown. A temporary walkway (yellow) will be in place during integration. Right Panel: The optical subsystems mounted on the TABL. The ENCL is designed by Quantum Technology and the TABL is designed by Sightline Engineering.

Next, light passes through the deployable NFIRAOS source simulator subsystem (NSS), which comprises two units: the six LGS sources; and the NGS source and focal-plane mask (FPM). Light is then further reflected off three off-axis paraboloids (OAPs) and the two deformable mirrors. DM0 is mounted in a tip-tilt stage (TTS). The second DM is referred to as DM11 as it is conjugate to an altitude of 11.8 km.

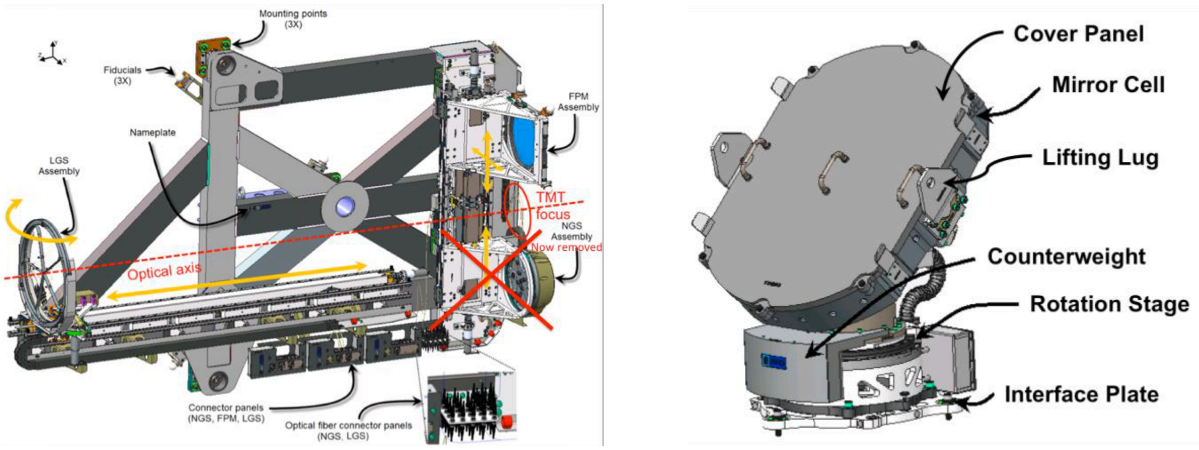

Figure 5: Left Panel – NFIRAOS Source Simulator (NSS). Note that to simplify the design and reduce costs, a single figure source will be mounted below the Focal Plane Mask (FPM) assembly and the carriage containing the NGS assembly will be removed. Right Panel – Instrument Selection Mirror (ISM) will direct light to one of three NFIRAOS output ports. Both the NSS and ISM were designed by Institut National d'Optique (INO).

The science beamsplitter transmits long-wavelength light to the infrared science-instrument path and reflects shorter-wavelength visible light to the LGS and NGS paths. The NFIRAOS beamsplitter (NBS) mechanism selects two different optics: a dichroic for the near-infrared science mode, and an intensity-splitter for engineering mode used with the alignment telescope.

At the end of the science path, the OAP4-S mirror refocuses the light, and the instrument-selection mirror (ISM) directs it to one of three instrument ports. Each port has a gate valve controlled by the ENCL, which seals NFIRAOS during instrument changes. The NSEN can be mounted on any of the three ports. It contains a high-resolution wavefront sensor (WFS), a diffraction-limited camera, and an acquisition camera.

The visible light reflected by the NBS is split into the visible natural light and the narrow-band laser light by the LGS beamsplitter. The laser light is re-imaged by its private copy of the OAP4-S mirror (OAP-4L) and directed into the LGS WFS subsystem. Sodium-range distance is compensated on the six LGS WFSs by the LGS trombone.

Visible light (600 nm–800 nm) from an NGS is refocused by OAP-4V and sent to the visible NGS wavefront sensor (VNW) sub-system. The VNW has a star-selection mechanism consisting of X–Y stages carrying a bench with focus and pupil steering stages, an atmospheric dispersion compensator (ADC), and camera. The coordinated motion of these stages aligns the pupil and the image on a pyramid wavefront sensor (PWFS) and corrects for the sag of the input focal plane. The NGS light is reflected by a fast steering mirror (FSM) that dithers and modulates the NGS light around the tip of the pyramid.

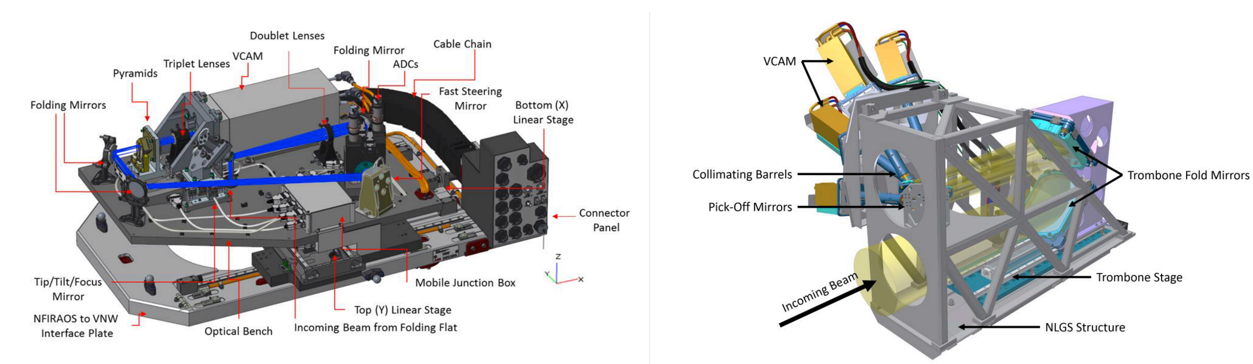

Figure 6: Left Panel – Visible Natural WFS (VNW) contains a Pyramid WFS that can patrol and track a star through the 2′ field. VNW was designed by ABB Bomem. Right Panel – LGS WFS consists of a trombone mirror assembly and six independent Shack-Hartmann WFS for each of the TMT LGSs.

Client instruments, including IRIS, are responsible for field de-rotation, atmospheric dispersion correction, and NGS tip/tilt/focus WFSing. IRIS achieves these aims by mounting the instrument on a large bearing that rotates both an enclosure that houses three OIWFS and a large science cryostat that houses filters, an ADC, a Lyot stop, the imager, and integral field spectrograph. The OIWFS consist of three probe arms that can patrol the 2′ NFIRAOS FOV and can deploy either an imager lens for tip/tilt sensing or a 2x2 lenslet array for tip/tilt/focus sensing. The IRIS OIWFS system is designed to use a SAPHIRA NIR APD[9], which enables guide-star sharpening by NFIRAOS and vastly improved sky coverage.

3.3 Software Design Overview

TMT software is organized in a hierarchy: at the top is the executive software (ESW) that commands various lower-level software components. For each phase of an observation, the ESW sends top-level commands to the telescope control system (TCS), the instrument sequencer and the AO sequencer (AOSQ) which is part of the AO Executive Software (AOESW). The AOESW consists of computers and software responsible for configuring, controlling, and coordinating subsystems for adaptive-optics observations. The AOESW has three subsystems: 1) the AOSQ which is responsible for setting up and coordinating the AO subsystems to acquire guide stars and deliver corrected wavefront to client instruments; 2) the NFIRAOS Real-Time Controller (NRTC) is the software and server hardware real-time control system that converts wavefront error measurements into wavefront corrector commands (Figure 7); 3) Finally, the RPG subsystem of AOESW interfaces with the NRTC to create and continually optimize the parameters (e.g., the control matrix) needed for AO correction of turbulence and vibration. The NFIRAOS component controller (NCC) comprises the computers, networking hardware, and software responsible for configuring, controlling and monitoring all low-speed electronics within NFIRAOS. These include the ENCL, the electronics enclosure, one-wire sensors, remote power bars, trigger-signal generators, motor controllers, piezo-actuator controllers, and remote I/O. At a high level, the NCC is configured by the AOSQ, which sequences the operation of the NCC and other AO subsystems.

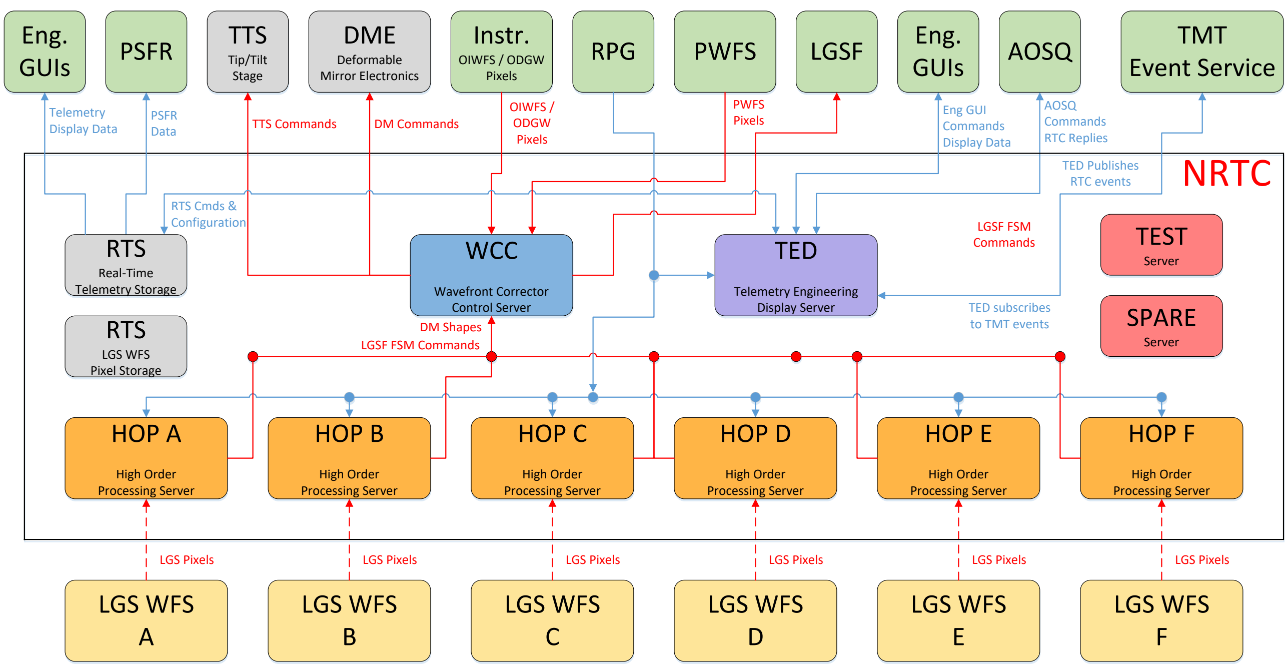

Figure 7: NFIRAOS Real-Time Controller (NRTC) includes 12 Xeon servers with 4 CPUs each.

3 PERFORMANCE BUDGETS

There are a dozen performance budgets for NFIRAOS. The top-level budget is the point source sensitivity budget that rolls-up the effects of several others including the AO WFE budget, throughput and background, pupil alignment, etc. In addition, NFIRAOS has budgets for NCPA and off-axis aberrations that affect the dynamic range on WFSs and sky-coverage respectively. There are tolerance budgets for: WFS camera alignment affecting registration to the DMs; DM stroke; astrometry and photometry; downtime; mass; cooling and power. We highlight some of our work on select performance budgets in this section.

3.3 Point Source Sensitivity

The point source-sensitivity-normalized (PSSN) budget is the top-level AO performance budget for the combination of TMT, NFIRAOS, and IRIS. Table 2 is a summary of the PSSN budget for the special case of on-axis imaging in K-band with IRIS. The terms in the budget multiply when they are combined. Each term is normalized relative to a perfect 30 m telescope without atmospheric turbulence and is inversely proportional to the integration time needed to image a background-limited point-source on sky. High-order wavefront error (WFE) degrades PSSN proportional to Strehl ratio-squared, while low-order WFE (errors controlled by OIWFSs) cause PSSN to drop with the Strehl ratio. Throughput losses (including science detector quantum efficiency) reduce PSSN proportionally. Pupil alignment turns out to be a critical term. IRIS contains an undersized pupil stop to prevent thermal radiation from the dome floor or telescope structure from reaching the imager. Originally, the requirement on the alignment tolerances between the telescope structure and the IRIS Lyot mask was set at 1% since this was tighter than the tolerance used at Gemini Observatory. However, it was found that a 2% undersizing of the pupil reduced the PSSN by more than 30%. This loss is due to two factors: an undersized pupil blocks light from reaching the imager focal plane, and it also broadens the PSF by reducing the effective diameter of the telescope. This led the involved teams to re-evaluate this requirement and tighten the pupil alignment budget so that the Lyot mask will only be undersized by 1% which leads to the 12.5% loss shown in Table 2. With NFIRAOS and the IRIS OIWFS enclosure cooled to -30° C, the thermal background is a small term in the overall PSSN budget. If NFIRAOS were not cooled, this term would be <0.4 (for K-band spectroscopy). Minor terms include image-smearing from mechanisms like rotators and ADCs; pupil-amplitude non-uniformity from atmospheric scintillation and M1 sequential recoating; and ghosts from windows and other transmission optics, such as beamsplitters.

Table 2: Summary of PSSN Budget for K-band, On-axis, IRIS imager

	PSSN Total	**Item**
PSSN NFIROS+IRIS	0.161	
Wavefront Error		0.592
Throughput		0.328
Pupil Alignment		0.875
Background		0.958
Image Smearing		0.997
Amplitude non-uniformity		0.994
Ghosting		0.994

3.3 Wavefront Error Budget

The TMT AO and NFIRAOS teams have put a great deal of effort into defining the Wavefront Error (WFE) budget over the past decade[3]. More than 60 terms have been considered and analyzed. The WFE budget is organized with a systematic approach. It is grouped by low and high-order modes: the low-order modes contain tip-tilt, plate scale, and focus modes that are controlled by the low-order OIWFS; and the high-order modes contain the remaining modes, which are controlled by the LGS WFS. Within each group, the error sources are categorized using the WBS structure down to level 3 systems. WFE is specified for both on-axis and field-averaged for 34 × 34 arcsec^2 cases. This field of view matches the new, larger IRIS imager field of view (which was just 16 x 16 arcsec^2 at PDU). The on-axis performance assumes the AO system is optimized for the larger 34 × 34 arcsec^2 field of view, which helps sky coverage by increasing guide star sharpening across the 2 arcmin diameter NFIRAOS field of view. This results in DM-projection error terms for on-axis performance. The contributions of NFIRAOS and IRIS have both been thoroughly updated based on design progress. The result of this major effort is that we expect TMT+NFIRAOS+IRIS to deliver a WFE of 207 nm RMS (more than 50% Strehl ratio in H-band) in median conditions at zenith. This budget is dominated by 188 nm RMS of high order WFE and 83 nm RMS of low order WFE (with 27 nm RMS of contingency).

In the high-order mode WFE budget, notable refinements in the budget include:

- Thorough AO performance simulations that include evolving sodium and turbulence profiles, reference matched filter updates incorporating the RPG functionality and updates to the LGS reference vector as obtained from the truth-WFS.
- We improved the breakdown of fundamental errors over the new wider IRIS field of view and a slightly higher DM conjugation altitude (11.8 km). The impact on WFE due to computing and using a reconstruction matrix instead of iterative algorithms for tomography and DM fitting has also been evaluated.
- Pupil distortion and misregistration due to telescope/NFIRAOS optics design and alignment errors have been thoroughly analyzed, which has also helped establish alignment tolerances of the LGS WFS camera.
- The performance impacts of optics polishing errors and lenslet defects have been estimated.

The dominant high-order WFE are due to the AO architecture (143 nm RMS) due primarily to fitting, projection and tomographic errors, NFIRAOS opto-mechanics (62 nm RMS), DM effects such as flattening errors, hysteresis and failed actuators (51 nm RMS) and terms associated with the LGS WFS such as signal variability, and lenslet throughput and aberrations (44 nm RMS).

Sky coverage (i.e. meeting low-order WFE budgets) has been evaluated over different Galactic coordinates and telescope zenith angles[5,6]. The expected low order WFE was decreased after recently switching the IRIS OIWFS detector from the Teledyne H1RG to the Leonardo APD array. The NIR APD can be read out faster with a smaller readnoise which improves overall performance. In particular, the OIWFS+NFIRAOS will be better able to cancel out telescope mechanical broadband vibration. Without vibration, the median sky-coverage optimal frame rate is around 80 Hz–90 Hz; but with vibration, the low read-noise APD array permits the median rate to increase to 400 Hz, which significantly improves vibration rejection and decreases the overall residual, despite the inevitable increase in noise propagation, which penalizes residual atmospheric tip-tilt and plate scale errors. Under median atmospheric conditions with the telescope pointing at zenith at a field with the stellar density of the North Galactic Pole, the low order WFE is expected to be 83 nm RMS or less 50% of the time. Given the large aperture of TMT, the guide star sharpening provided by the NFIRAOS MCAO system and the NIR OIWFS in IRIS, sky coverage will be very good all over the sky. Even in those cases where this error budget is not meant because the available guide stars are not sufficiently bright or numerous, NFIRAOS can still achieve a somewhat degraded, but still useful, performance a large majority of the time by using fewer than 3 OIWFS targets or by running the OIWFS slower while targeting fainter NGS.

3.3 Astrometry, Photometry and PSF Reconstruction

TMT has a top-level requirement to achieve differential astrometry with an accuracy of 50 μas in a 100 s exposure in H-band, falling proportionally as $T^{-0.5}$ (where T is integration time) to a systematic floor of 10 μas. It is understood that this requirement is to be met in science fields with many objects, such as the Galactic center. The achievable accuracy depends on the observatory performance and the properties of the science fields and targets. We have therefore developed a detailed astrometry error budget[8] to assess the following goals:

- Determine the impact of the different subsystems on TMT astrometry accuracy and the error terms they produce.
- Figure out whether show stoppers prevent us from achieving the required accuracy.
- Determine what accuracies can be achieved for different types of science cases.

We have analyzed more than 30 error terms to assess their impact on TMT astrometry. Many of these terms depend on the individual science case (e.g. brightness and crowding of targets). Others terms are dependent on the science instrument (e.g, detector characteristics or filter properties). Early analysis of the astrometric error budget identified a potential show-stopper in terms of achieving high precision astrometry with NFIRAOS. The NFIRAOS Preliminary Design used a conventional 2 OAP optical relay that induced some distortion. This distortion, however, would rotate as IRIS was tracking the sky rotation. Even a small rotating distortion field elongates the point spread function (PSF) differently across the science field. Coupled with small changes in atmospheric conditions and the AO correction or changes in transmissivity of the atmosphere, this distortion from NFIRAOS set the tall pole in the astrometric error budget which would prevent 50 μas precision. This led to a major revamping of the NFIRAOS design before the final design phase commenced in which the 2 OAP relay was eventually replaced by a 4 OAP relay that could produce a distortion-free focal plane for the instruments. With that change, NFIRAOS will not limit the astrometric accuracy achievable by TMT; the astrometric error budget shows that accuracies of 50 μas are achievable as long as there are enough sufficiently bright stars available in the field.

TMT+NFIRAOS+IRIS are also required to deliver excellent flux measurements (photometry). The photometric accuracy and precision is even more dependent on the distribution of sources in the field. NFIRAOS (and indeed, any AO system), can affect the PSF out to the control radius (~0.35″ in H-band). To be able to maximize the photometric accuracy, the PSF should be well-understood out to that distance[10]. For IRIS, that corresponds to roughly to PSF knowledge over 170 x 170 square pixels. While this PSF knowledge could be difficult to come by, we have concluded that all measures taken to ensure high-precision astrometry will benefit photometry as well.

This quest for PSF knowledge has led to in-depth studies of PSF reconstruction (PSFR) by the TMT AO group. We have investigated the limitations of reconstruction PSFs from AO telemetry, based on NFIRAOS simulations[11]. PSFR can benefit many astronomical science cases, but the relationship between the PSF uncertainty and the error in the astronomical quantity of interest is not trivial and depends on the science case. We are planning realistic science case investigations for NFIRAOS+IRIS to ensure that both the required telemetry data and the data analysis software and procedure are in place to utilize the power of these instruments.

4 CONCLUSION

The NFIRAOS project successfully completed its Final Design Review in June 2018. Involving industry in the final design has enhanced the quality of the design and removed risk and uncertainty from the project entering the fabrication phase. In these proceedings, we have also discussed how NFIRAOS requirements and performance budgets have driven the NFIRAOS design to improve over time. The decisions to cool NFIRAOS to -30° C, to tighten the pupil registration, and to redesign the OAP relay to remove distortion all added cost and complexity to the instrument, but are all well-motivated by the eventual scientific performance gains.

NRC HAA is prepared to initiate the fabrication phase of NFIRAOS once construction of the telescope begins at the site. We are taking advantage of this time before fabrication begins to address some outstanding design work such as the design of the DM electronics now that TMT has chosen a DM vendor and completing the final design of the NSEN while taking advantage of a similar design for the top-end of the IRIS instrument. Once fabrication commences, it will take roughly 4 years to have all the completed subsystems on site in Victoria. NFIRAOS will be completely assembled and tested in Victoria in a new NRC integration facility. Eventually IRIS will also be integrated in Victoria and NFIRAOS and IRIS will be tested together before being shipped to TMT. We are developing a detailed plan with TMT to efficiently re-assemble NFIRAOS on the TMT Nasmyth platform. NFIRAOS will be integrated with the rest of TMT and IRIS and should be ready to be the workhorse instrument for TMT first light.

REFERENCES

[1] Herriot, G., Andersen, D., Atwood, J., et al., "NFIRAOS: first facility AO system for the Thirty Meter Telescope," Proc. SPIE 9148, id. 914810 (2014).

[2] Crane, J., Herriot, G., Andersen, D., et al., "NFIRAOS adaptive optics for the Thirty Meter Telescope," Proc. SPIE 10703, id. 107033V (2018).

[3] Wang, L., Ellerbroek, B., Herriot, G., Véran, J.-P., & Boyer, C. "Optimizing multi-LGS WFS AO performance in the context of sodium profile evolution and non-common path aberration," Proc. SPIE 10703, id. 107032B (2018).

[4] Larkin, J.E., et al., "The Infrared Imaging Spectrograph (IRIS) for TMT: instrument overview," Proc. SPIE 9908, id. 99081W (2016).

[5] Andersen, D., Wang, L., Ellerbroek, B., & Herriot, G., "Predicted sky coverage for the TMT MCAO system NFIAOS," in Second International Conference on Adaptive Optics for Extremely Large Telescopes (AO4ELT2), 18, (2011).

[6] Wang, L., Gilles, L., Ellerbroek, B., & Correia, C., "Physical optics modeling of sky coverage for TMT NFIRAOS with advanced LQG controller," Proc. SPIE 9148, 91482J, (2014).
[7] Andersen, D. R., Herriot, G., Ellerbroek, B., & Hickson, P., "Scientific Impact of the Operating Temperature for NFIRAOS on TMT, in Adaptative Optics for Extremely Large Telescopes, 01006 (2010).
[8] Schöck, M., Do, T., Ellerbroek, B. L., et al., "Thirty Meter Telescope astrometry error budget," Proc. SPIE 9148, 91482L, (2014).
[9] Finger, G., Baker, I., Alvarez, D., et al., "SAPHIRA detector for infrared wavefront sensing," Proc. SPIE, Vol. 9148, 914817, (2014).
[10] Turri, P., McConnachie, A.W., Stetson, P.B., et al., "Optimal Stellar Photometry for Multi-conjugate Adaptive Optics Systems Using Science-based Metrics," AJ, 153, 199 (2017).
[11] Gilles, L., Wang, L., Boyer, C., "Point spread function reconstruction simulations for laser guide star multi-conjugate adaptive optics on extremely large telescopes," Proc. SPIE, 10703, 1070349 (2018).