NFIRAOS Pre-Production Optical Design Update

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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 optical manufacturing specifications are key to achieving the performance requirements for NFIRAOS. Here we present the flow-down of science requirements to the derived manufacturing and assembly tolerances.

As NFIRAOS approaches the build phase, we plan to purchase a first article off-axis paraboloid (OAP) mirror. The plans for testing and alignment are presented, along with plans for integrating sub-systems into NFIRAOS using laser trackers and spherically mounted retro-reflectors (SMRs). The final alignment step will use an automated alignment telescope, sighted on alignment fiducials on the optics, and deployed outside the NFIRAOS entrance window.

Keywords: Adaptive Optics, TMT, NFIRAOS, Optical Design, Alignment

1. INTRODUCTION TO NFIRAOS

NFIRAOS (Narrow Field InfraRed Adaptive Optics System, pronounced nefarious) is the first-light adaptive optics system for the Thirty Meter Telescope (TMT). It is an ambitious Multi-Conjugate AO (MCAO) system feeding science light from 0.8 to 2.5 microns wavelength to three near-IR client instruments (Figure 1). NFIRAOS sits on a support structure above the Nasmyth platform; the thermal enclosure houses the optical TABL and regulates the internal temperature to -30 C. NFIRAOS provides a diffraction-limited, 2 arcminute field of view (FOV) to the science instruments. 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.[1,2] Sky coverage is also a key performance metric. Six laser guide stars (LGS), 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.[3,4] This sky coverage fraction increases dramatically for fields closer to the galactic plane where many more stars are available.

The NFIRAOS block diagram is shown in Figure 2. Telescope light enters NFIRAOS through its entrance window and then passes by the deployable NFIRAOS source simulator, which comprises two units: the six Laser Guide Star (LGS) sources; and the Natural Guide Star (NGS) source and focal-plane mask. Light is then further relayed off three OAPs and the two deformable mirrors (DMs). These two DMs are optically conjugate to 0 m (ground) and 11km above TMT. DM0 is mounted in a large Tip-Tilt stage (TTS) that can be used to compensate for atmospheric tip-tilt, windshake and vibration. A science beamsplitter transmits long-wavelength light to the infrared science-instrument path and reflects shorter-wavelength visible light to the LGS and NGS WFS paths. At the end of the science path, a final OAP refocuses the light, and the instrument selection mirror directs it to one of three instrument ports. The visible light reflected by the beamsplitter is split into the visible light (600-800 nm) and the narrow-band laser light (589 nm) by a second beamsplitter. The laser light is reimaged by its own private copy of the final OAP mirror and directed into the LGS WFS subsystem. The six LGS WFS detectors stream pixels to the RTC to drive the DMs and tip/tilt stage. Visible light from an NGS is refocused by another copy of the final OAP and sent to the visible NGS WFS labelled as a Pyramid WFS. This WFS can be used when LGS are unavailable or can act as a slow truth or fast tip-tilt NGS WFS in MCAO mode.

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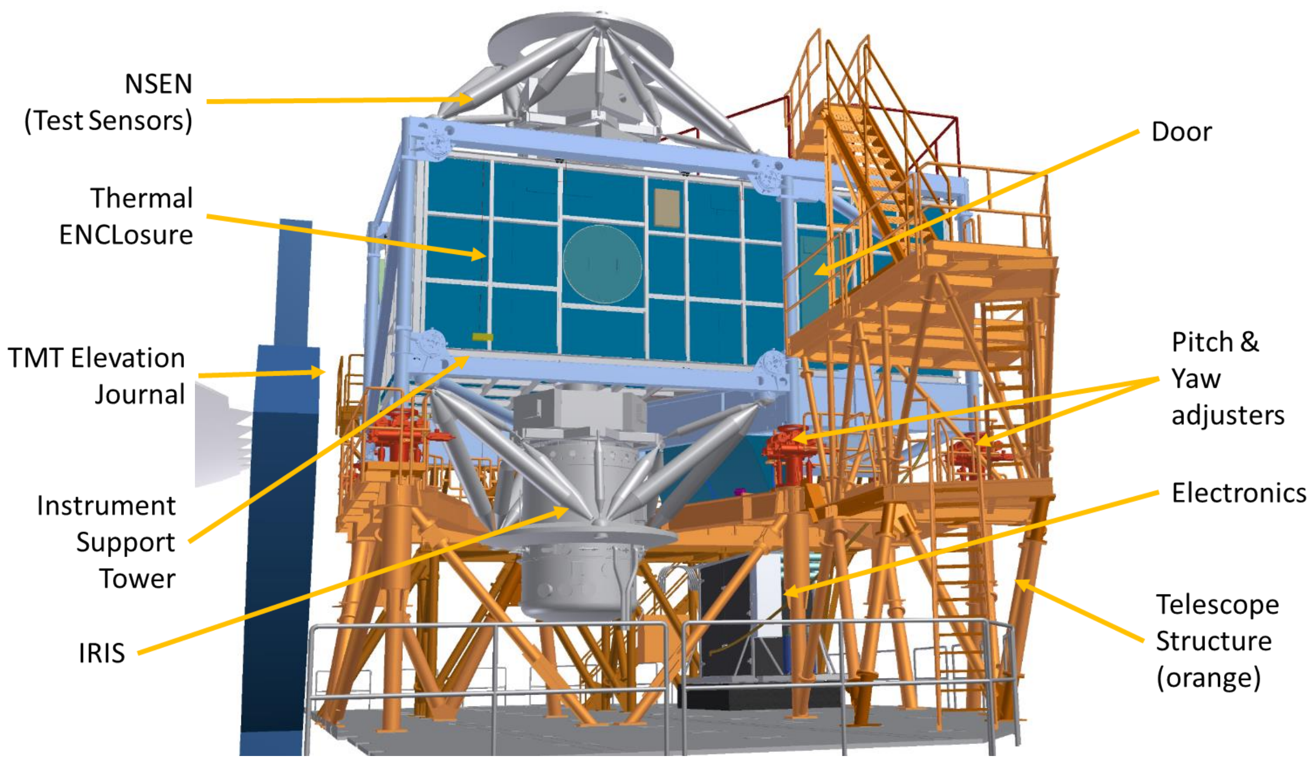


Figure 1. NFIRAOS shown on the Nasmyth platform. The TMT primary mirror elevation journal can be seen on the left. IRIS, a first light instrument, is shown on the bottom port. Instruments may also be installed on the top or side ports.

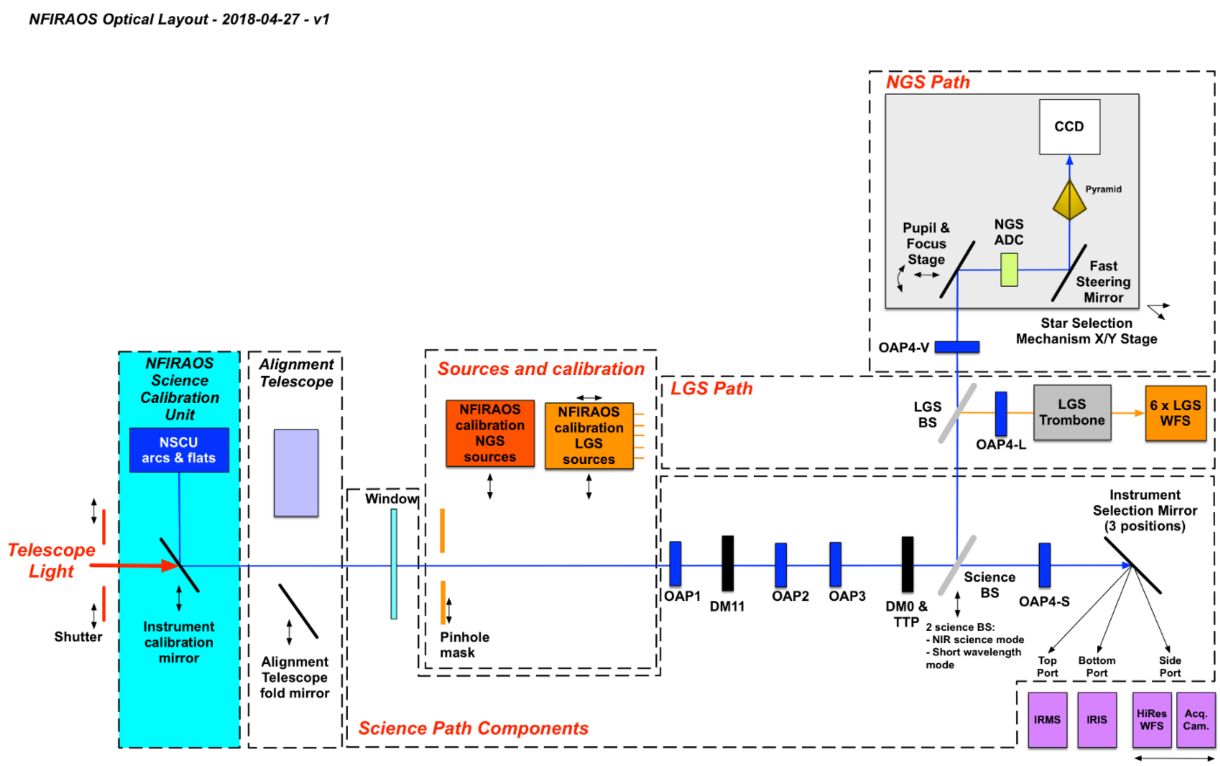


Figure 2. NFIRAOS block diagram.

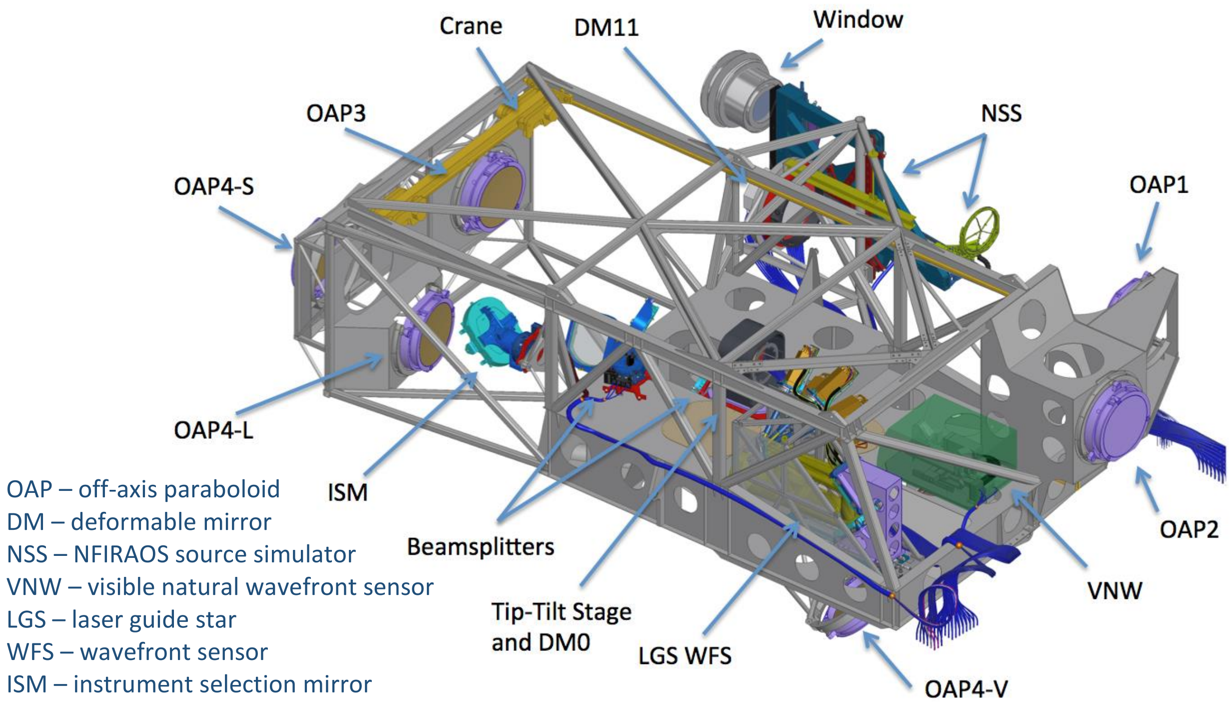


Figure 3. The NFIRAOS optical bench (TABL) inside the cooled enclosure. The TABL supports 6 OAPs and many additional optical assemblies.

The NFIRAOS functionality and performance has been captured in roughly 400 detailed requirements that have been driven by numerous performance budgets and studies. These requirements have been flowed down to each of the sub-systems and are used to guide the design, build and verification activities. NFIRAOS performance budgets are used side-by-side with TMT performance budgets to track performance across NFIRAOS and TMT subsystems. As an example, the TMT wavefront error budget includes terms applicable to NFIRAOS, M1/M2/M3, IRIS, dome seeing and windshake, and vibration.

In preparation for the Final Design Phase, 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, including the OAPs, NSS and VNW (Figure 3). 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 completed its FDR in June, 2018. The team now is continuing with some remaining design and analysis work while we wait for TMT construction to commence. When TMT breaks ground, NRC-HAA will kick off its fabrication phase and re-engage with our Canadian industry partners to fabricate, assemble and test individual NFIRAOS subsystems. NRC is already actively building an integration facility in Victoria that can be used to assemble, integrate and test TMT instruments, including NFIRAOS and IRIS. As Canadian industry delivers NFIRAOS subsystems to Victoria, NFIRAOS will be assembled. We will be able to test and verify most the NFIRAOS requirements in Victoria before it is disassembled and shipped to TMT for integration with the telescope.

2. REVIEW OF REQUIREMENTS

2.1 Top-level Requirements

TMT uses the DOORS database to track all observatory requirements. The TMT Level 1 requirements are captured in the Observatory Architecture Document (OAD). Each major subsystem within TMT, such as NFIRAOS, has a Level 2 Design Requirements Document (DRD). NFIRAOS has further partitioned requirements into Level 3 DRDs for each of the subsystems. NFIRAOS also has developed a Common Standards document to define requirements that span across multiple subsystems. Each requirement in TMT is formatted as follows: REQ-#-XXXX-####. The first number refers to the requirement level (1, 2, etc). The characters refer to the applicable system; all NFIRAOS subsystems begin with N. The final numbers are the requirement numbers.

The driving requirements for NFIRAOS (Table 1) are derived from Level 1 requirements.

Table 1: Level 2 NFIRAOS requirements that drive the optical design

Requirement		Value	Comment
REQ-2-NFIRAOS-0670	Science Wavelengths	0.8 – 2.4 μm	
REQ-2-NFIRAOS-0690	Field of View	2 arcminutes	Goal 2.6 amin
REQ-2-NFIRAOS-0660	Throughput	> 80% > 60%	1-2.4 um 0.8-1 um
REQ-2-NFIRAOS-0730	Zenith Angle	0-65 deg	Equiv to 85-235 km sodium range
REQ-2-NFIRAOS-0750	Photometry	0.1%	1 um, 30 asec FOV, 10 minutes
REQ-2-NFIRAOS-0760	Astrometry	<15.5 uasec	H band, 30 asec FOV, 100 seconds
TMT Performance Budget	Wavefront error	< 193 nm RMS on-axis	Including TMT and instruments in LGS MCAO mode

2.2 Traceability and Performance Budgets

For each requirement in the NFIRAOS DRD, we have created connections to Level 1 and Level 3 requirements. The Level 1 to Level 2 connections are captured in DOORS. Excel sheets with Python scripts are used to create and track Level 2 to Level 3 connections. We use these tools to ensure that all Level 2 requirements are properly reflected in Level 3 requirements, and to ensure that all Level 3 requirements are appropriately derived from Level 2. Once we begin to verify requirements, this traceability will be used to show that all requirements have been met.

Figure 4 shows the traceability for the Throughput requirement. This requirement at Level 2 is derived from a specific Level 1 requirement. Within the NFIRAOS DRD we then allocate a portion of the total budget to each of the optics. These allocations are then used to create requirements within each Level 3 subsystem. The requirements define a top-down value for throughput for each optic. A bottom-up estimate of the throughput performance is captured in the NFIRAOS throughput budget (Figure 5). The values in the throughput budget are derived from coating designs or coating prototypes.

Additional performance budgets within NFIRAOS and TMT also function in this manner. The Normalized Point Source Sensitivity budget (PSSN) summarizes the terms that affect observing time for unresolved point sources, such as pupil mask under-sizing or background light due to scattering, throughput, etc. The LGS slope budget is used to collect terms that affect the location of the Shack-Hartmann spots on the detector, such as residual WFE or alignment of the lenslet array to the CCD. The DM stroke budget controls how much DM stroke can be used to correct for various static and dynamic errors.

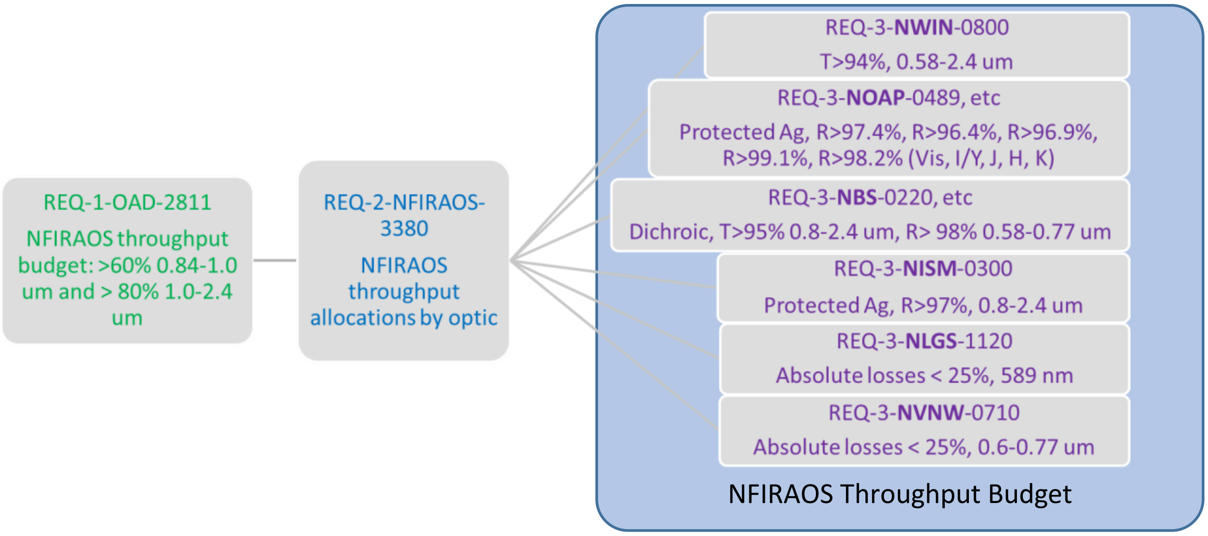


Figure 4: Traceability for the NFIRAOS Throughput requirement from Level 1 to Level 3.

	LGS	VNW	I/Y-band	J-band	H-band	K-band
Requirement	60 75%*80%	60 75%*80%	60	80	80	80

	Typical Throughput					
	LGS	VNW	I/Y-band	J-band	H-band	K-band
	0.589	0.6-0.75	0.8-1.0	1.1-1.4	1.45-1.85	1.9-2.45
Total optical transmission	0.685	0.576	0.691	0.819	0.846	0.840
NFIRAOS Contamination losses	0.963	0.951	0.975	0.975	0.975	0.975
Science path optics	0.809	0.777	0.709	0.840	0.868	0.861
Input Window (2)	0.922	0.867	0.867	0.961	0.961	0.980
OAP1	0.978	0.982	0.973	0.987	0.991	0.986

Figure 5: NFIRAOS throughput requirement (top) and an excerpt from the Throughput Performance Budget (bottom) giving the current best estimate.

3. PLANS FOR INITIAL PROCUREMENT

NFIRAOS passed its Final Design Review in December 2018. An additional Optical Production Readiness Review was held in July 2019. The Optical PRR was held in anticipation of purchasing a first-article OAP. The OAPs are the heart of the optical design, and a long-lead item, making them an obvious choice for early procurement. The full opto-mechanical procurement of a first-article is expected to take up to 18 months. Currently, this procurement kickoff is awaiting TMT construction progress. The OAP design is shown in Figure 6.

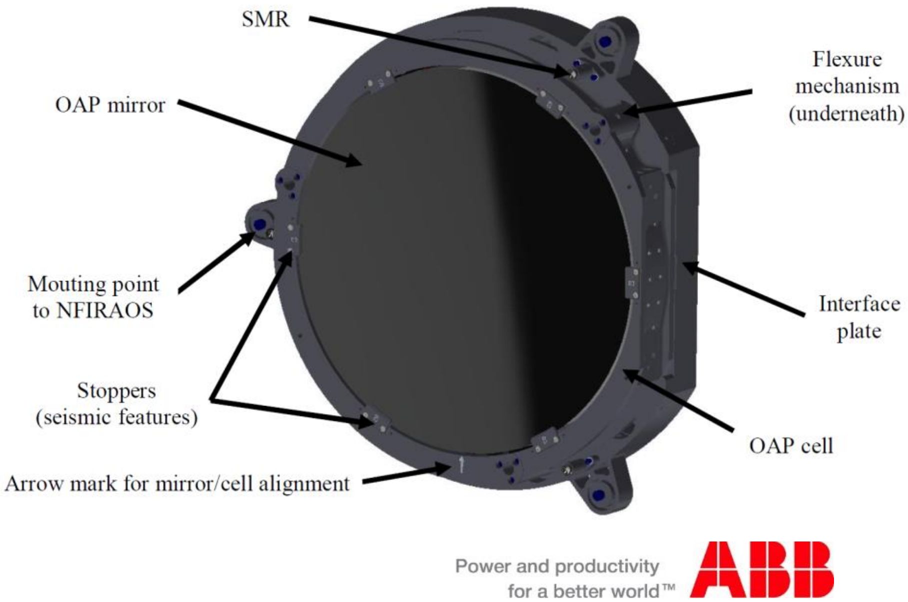


Figure 6: NFIRAOS Off-Axis Parabola subsystem. NFIRAOS is planning early procurement of a 1st article OAP.

At these two reviews, we showed that our requirements are well understood and we have allocated our budgets to the sub-system level with sufficient detail. We have created optical drawings for the OAP optics and mounts based on multiple analyses. In order to determine the surface specifications for the optics, we have investigated how optical polishing errors affect performance using a power spectral density (PSD) analysis (Figure 7). The polishing techniques used change the slope of the PSD curve, and therefore the resulting RMS wavefront error (WFE). We were able to divide and balance our budget of 35 nm RMS uncorrectable error between each of the optics. The resulting values for each optic as a function of PSD slope (p) are shown in Table 2. It can be seen that the lowest WFE values are around 24 nm RMS. As this is not an unachievable requirement, it simplifies the requirement to use 24 nm RMS, independent of polishing method.

Using 24 nm RMS at the top level requirement for the OAPs, we can then partition that value in quadrature between optical fabrication (15 nm), mounting/ thermal effects (15 nm) and contingency (10 nm). Finite Element Analysis performed by ABB showed that the mounting and thermal designs would meet the allocation, with additional contingency. These results are shown in Table 3.

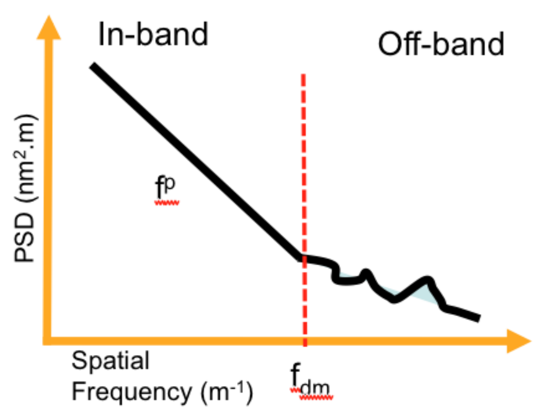


Figure 7: A typical Power Spectral Density curve (PSD). The slope exponent (p) is a parameter that is dependent on the polishing technique.

Table 2: Optical surface errors (nm RMS) for each NFIRAOS optic as a function of PSD slope parameter (p).

Optical Surface	Tolerable wavefront error (nm rms) on the full aperture (metapupil)						
	p=-1	p=-1.5	p=-2	p=-2.5	p=-3	p=-3.5	p=-4
TOTAL	**68.7**	**69.3**	**72.1**	**77.6**	**87.6**	**104.9**	**127.8**
WIN 1 -191.1km	24.4	24.9	26.9	31.4	39	51	65.9
WIN 2 -198.2km	24.3	24.8	26.9	31.5	39.3	51.7	68.9
OAP 1 49.2km	24.3	24.3	24.7	25.5	26.7	29.2	32.2
OAP 2 -36.6km	24.2	24.2	24.5	24.9	25.9	28.1	30.9
OAP 3 35.2km	24.3	24.3	24.7	25.3	26.4	28.9	31.8
B/S -9.7km	24.3	24.7	26	27.9	31	36.2	42.1
OAP 4 43.6km	24.1	24.1	24.4	24.6	25.6	27.6	30.3
ISFM -85.2km	24.4	24.7	25.7	27.5	30.2	34.5	39.4

Table 3: ABB analysis of the OAP mount for Wavefront Error. The estimates are well within the 15 nm allocation.

Contribution	Mechanical P-V (nm)	Mechanical RMS (nm)	Optical RMS (nm)
Mounting – Horizontal OAP mirror in OAP cell (passive pneumatic)	0.91	0.17	0.34
Mounting – Vertical gravity loading (worst case)	15	3.24	6.48
Mounting – Inclined gravity loading (worst case)	13.5	2.50	5.00
Mounting – 1 mrad OAP Tilting (worst case)	2.29	0.48	0.96
Thermal loading (worst case) – 20°C to -30°C excursion	1.12	0.27	0.54
WFE Summation – Vertical WFE Summation - Inclined	-	4.16 3.42	8.32 6.84

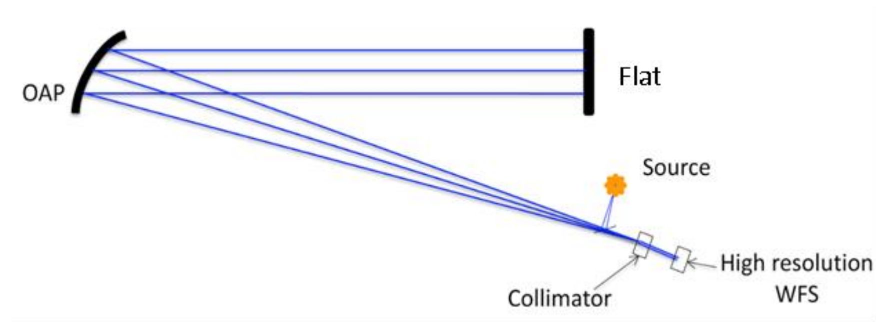
- Power terms are not included

4. TEST AND INTEGRATION PLANS

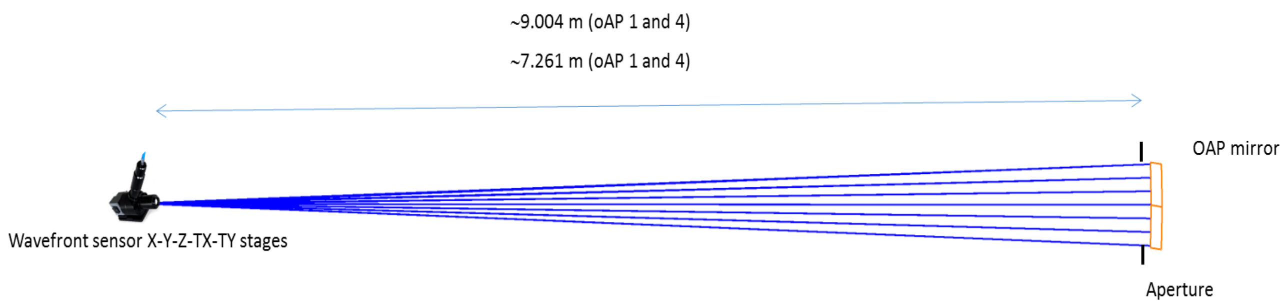
4.1 OAP Testing

NRC plans to procure the OAP optics and provide them to ABB for mounting. This type of partnership will require a clear understanding of the testing plans at the optical manufacturer, at ABB and at NRC. We have developed testing procedures for the OAPs at each step of the process (Figure 8). In discussions with optical polishers, we are planning for the initial tests at the manufacturing facility to be a conventional "null" test using a return flat in double-pass. This method is preferred because it does not rely on additional components (CGH) or calibrations to verify the WFE. However, it does require an expensive return flat. During this test, we will verify the surface figure, off-axis distance and radius of curvature.

During assembly, ABB will be verifying that their mounting methods do not distort the optics. This is a relative before/after test, so we have suggested a "center of curvature" test with a HASO WFS. This test requires little equipment beyond the WFS, but does require a long linear area. We plan to use this test at the optical manufacturer to compliment the "null" test and to set a baseline for ABB. ABB will then use the test at their facility repeatedly during the integration of the OAPs with the mounts. The measurements will identify changes in the surface figure after mounting. This test cannot be used for absolute measurements as it has considerable astigmatism and coma.



(a)



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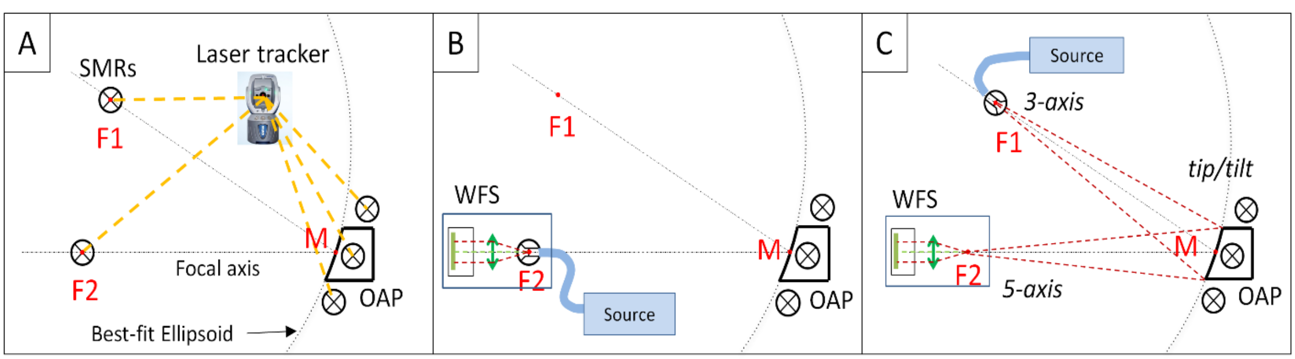

(c)

Figure 8: Testing methods for the OAPs. (a) “null” test at the manufacturer, (b) “center of curvature” test at ABB, and (c) “elliptic test” at NRC.

The final OAP tests are done in their mounts at NRC. The goals of this test are two-fold: first we verify the off-axis distance, radius of curvature and surface quality, second we create a local coordinate system for the optic to be used in integration. We have developed a test we call the “elliptic test.” This test approximates the OAP as an ellipse and uses two foci for the testing. The advantage of this test is that it does not require a large return flat like the “null” test. However, it still has residual aberrations. The magnitudes of these residual aberrations can be used to calculate parameters like the off-axis distance and radius of curvature. As a result of the Optical PRR, it was determined that the “elliptic” test and HASO 128 were not going to be sufficient to derive the off-axis distance and radius of curvature values from the measured aberrations with the required accuracy. A detailed trade study has led us back to the “null” test with a fizeau interferometer for final testing at NRC.

The final testing step is to create a coordinate system for the optic using the laser tracker and spherically mounted retro-reflectors (SMRs). Each subsystem is delivered with fixed SMRs and their locations relative to the physical center of the optic. For the OAPs, the chief ray intercept – not the mechanical center – determines the "center" of the optic. On an OAP, the chief ray intercept is determined by the as-built off-axis distance relative to the physical center of the optic, with respect to the focal point. In the "null" test, we use the location of the focal point, the OAP outer diameter, the plane of the return flat, and the location of a mask at the return flat to determine a coordinate system for the OAP. This coordinate system has an origin at the focal point with the Z axis parallel to the optical axis, which allows for easy import into the mechanical CAD model. This coordinate system is then used to make an alignment "mark" at the chief ray intercept on the optic. The mark is applied with a CMM to give an accurate position with respect to the mounting interface.

4.2 Subsystem Integration and OAP alignment

Integration of the optical subsystems onto the optical support structure (TABL) occurs in multiple steps. The first step is to use the as-built optical parameters to determine the desired location for each of the sub-system interfaces on the TABL. Each optic has an interface plate (IP) with three SMRs that are visible from the tracker (Figure 9). Step 2 is to use a laser tracker to position each interface plate to match the desired as-built location in XYZ. This is done via nudgers and shims to maintain stability. We can adjust the interface plates without the full weight of the assembly because each IP has a kinematic connection to the rest of the assembly. This way, when the full assemblies are installed on the interface plates, the optics will be in the correct location in XYZ to within 2 mm.

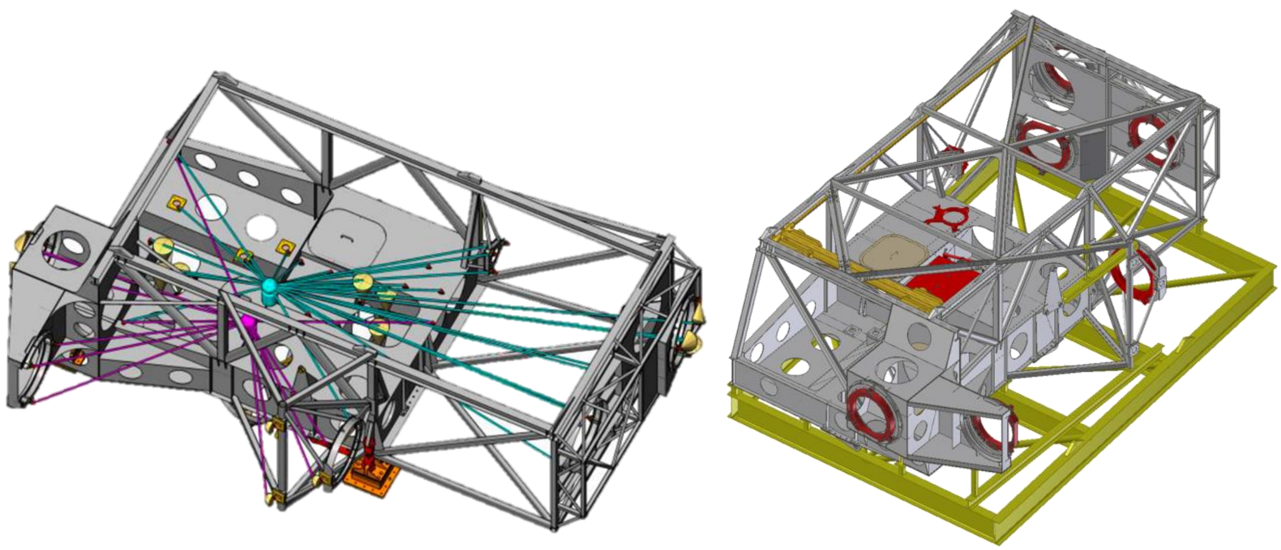

Figure 9: (left) A laser tracker is used to survey all the subsystem interfaces on the TABL. Two locations are shown to ensure three points on each interface can be seen. (right) Subsystem interface plates (IPs) are highlighted in red. Each IP can be positioned in XYZ to match the optical prescription.

Once all the interface plates are aligned, we install the optics. To accommodate flexure, the alignment does not begin until the TABL has been fully populated with actual subsystems or with dummy weights. The final step is the tip/tilt optical alignment. For flat optics, tip and tilt are only necessary to repoint the optical axis. However, for the OAPs, slight errors in centering can be compensated with tip/tilt without adding much residual aberration. Our approach revolves around a concept of marking the optics. The marks at the center of each optic create a line of sight from one optic to the next. By using tip and tilt, we can align the optical axis to these lines of sight.

NFIRAOS will have a dedicated alignment telescope (AT) mounted outside the entrance window. This AT has a variable focus adjustment that allows it to focus on each optical surface. The initial optical axis of NFIRAOS is defined by the central pinhole of the focal plane mask (FPM) in the NFIRAOS Source Simulator (NSS) and the mark on OAP1. The first step is to adjust the AT until its axis is coincident with the FPM-OAP1 line of sight. Next, the AT is focused on DM11 and the tip/tilt adjustment on OAP 1 is used to center the DM11 mark on the AT field of view (Figure 10). This process is repeated for each optic to the three focal planes (science, LGS, VNW).

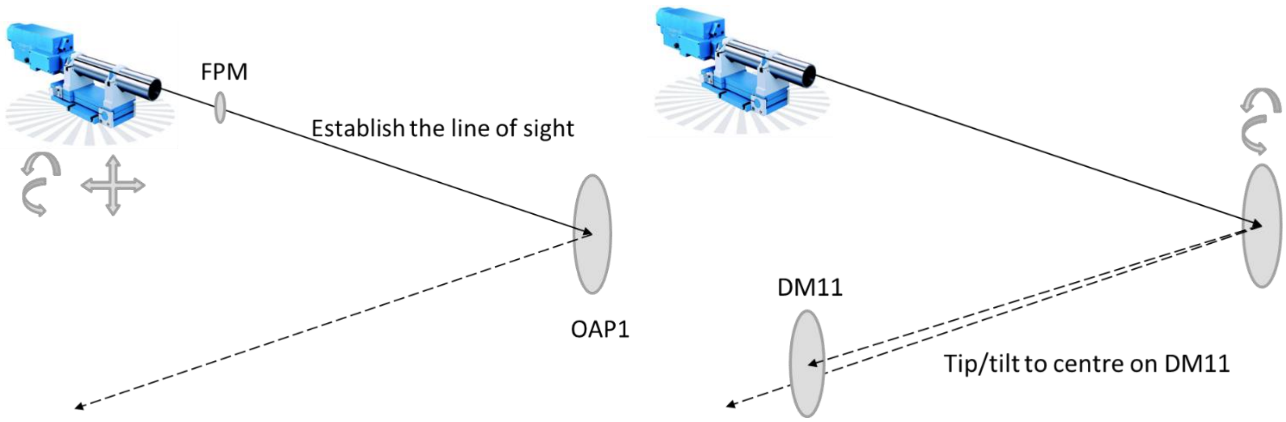

Figure 10: Tip/tilt alignment of the optics uses an alignment telescope (AT) to visualize marks on each optic. (left) The initial optical axis is defined as the line of sight between the NSS FPM and the OAP1. (right) DM11 is aligned by tip/tilting OAP1 until the AT is centered on the DM11 mark. This is repeated for subsequent optics.

5. CONCLUSION

Following the NFIRAOS Final Design Review and the Optical Production Readiness Review, we feel confident that we can move forward with procurement of the first Off-Axis Parabola. We have developed all the necessary requirements and flowed them down to the subsystem level. We have developed bottoms-up performance budgets and reconciled our best estimates with the top-down requirements. Our analyses show that we can expect to be within specifications for mounting OAPs, and we've developed testing methods to verify those specification. Our alignment plan has been developed to a detailed level and includes integration plans.

The next steps for NFIRAOS are pending the start of construction at TMT. Once it is clear that construction will commence, we plan to let the initial contract for the manufacture and assembly of the first OAP. We are currently making the last of our final design updates and preparations for the FAB phase. We anticipate revisiting some of our subsystem contracts to update requirements and implement design changes that arose during FDR. We are also finalizing costing and schedules for the upcoming phases.

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