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Optomechanical Design of TMT NFIRAOS Subsystems at INO

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ABSTRACT

The adaptive optics system for the Thirty Meter Telescope (TMT) is the Narrow-Field InfraRed Adaptive Optics System (NFIRAOS). Recently, INO has been involved in the optomechanical design of several subsystems of NFIRAOS, including the Instrument Selection Mirror (ISM), the NFIRAOS Beamsplitters (NBS), and the NFIRAOS Source Simulator system (NSS) comprising the Focal Plane Mask (FPM), the Laser Guide Star (LGS) sources, and the Natural Guide Star (NGS) sources. This paper presents an overview of these subsystems and the optomechanical design approaches used to meet the optical performance requirements under environmental constraints.

1. INTRODUCTION

NFIRAOS is a laser guide star Multi-Conjugate Adaptive Optics (MCAO) system that corrects the atmospheric turbulence using two deformable mirrors [1]. NFIRAOS is supported on a Nasmyth platform of the TMT and will deliver a 2-arcminute beam to three client instruments. Figure 1 shows an isometric view of NFIRAOS preliminary design where the subsystems discussed in this paper are indicated in bold. The first subsystem, starting from the input window, is the NFIRAOS source simulator. The NSS is operated for off-sky use to simulate the sources, as they will be seen on the sky, for alignment and calibration of adaptive optics system.

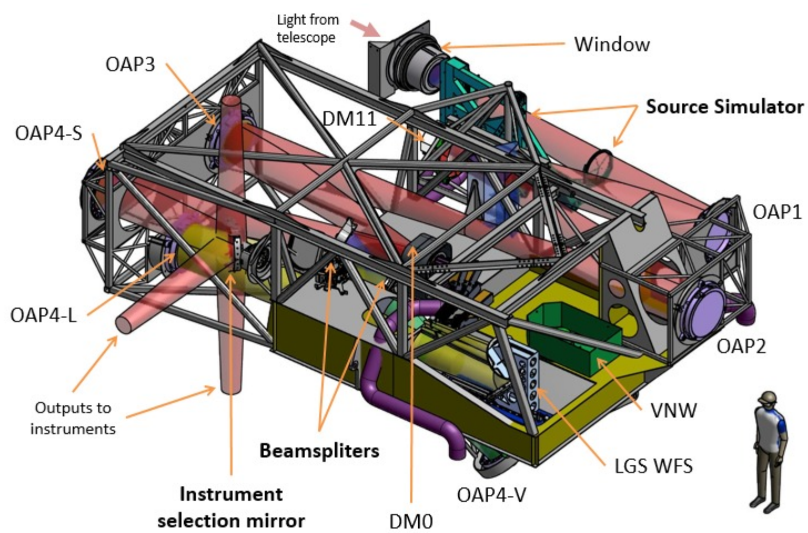

Figure 1. Isometric view of NFIRAOS preliminary design.

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The second subsystem is the NFIRAOS beamsplitters subsystem that includes a science and an engineering beamsplitter (BS) mounted on a changer mechanism. The changer mechanism allows the selection between the two BS during system integration and alignment. The light reflected from the science BS is directed to the visible light BS, which is stationary.

Finally, the third subsystem is the instrument selection mirror that moves between three positions to reflect the light to one of the three instrument ports.

In order to reduce the thermal background emissivity, NFIRAOS will be operated at -30°C. This presents challenges, especially for the motorized mechanisms and for the mounting of the large optical components. Special care shall be taken in order to maintain the alignment and minimize the wavefront (WFE) error at low temperature. The subassemblies shall also survive to temperatures from -45°C to +55°C as well as shipping, handling and seismic vibrations. The environmental requirements are presented below.

- Temperature Range:
  - Operational: 243 K to 293 K (-30ºC to +20ºC)
  - Survival: 228 K to 328 K (-45ºC to +55ºC)
- Vibration:
  - During observations, NFIRAOS may impart 0.5 μm RMS vibration (in arbitrary XYZ direction) over the range of 5-20 Hz into its subsystems.
- Handling:
  Subsystems shall be designed to withstand handling acceleration loads of 2.0 g vertical and 1.5 g horizontal.
- Shipping:
  - Subsystem shipping containers and sub-containers must withstand drops from a height of at least 200 mm, and withstand overturning accidents, without damaging any components.
- Seismic:
  - 10 year return period:
    - The subsystem shall withstand repeated exposure to frequent earthquakes up to the level of the 10-year return period event with no damage and with no degradation of performance, including alignment and repeatability functions.
    - Accelerations (worst case): 1.9 g
  - 200 year return period:
    - The subsystem shall be designed to withstand an infrequent earthquake up to the level of a 200-year return period event with no damage to optics or degradation of performance.
    - Accelerations (worst case): 3.0 g
  - 1000 year return period:
    - The subsystem shall be designed to protect optics from damage (except coatings) in the event of a very infrequent earthquake up to the level of a 1000-year return period event.
    - Accelerations (worst case): 4.4 g

2. NFIRAOS SOURCE SIMULATOR

The NSS consists in three optical subassemblies, the FPM, the LGS sources, and the NGS sources. The FPM and the NGS are both mounted on a vertical linear stage that allows to deploy and retract these subassemblies from the science optical beam. Both stages run on the same set of rails but have their own individual ball screws and drive mechanism. A pulley/counterweight system is used on each drive mechanism to prevent the motors from being used more than necessary. The LGS is mounted on a flip stage mechanism that allows to move the assembly in and out of the optical path. The flip stage is mounted on a linear stage that moves the sources along the optical beam axis. All three systems are mounted to a common frame which is then mounted onto NFIRAOS. The NSS subsystem dimensions are about

2650 mm x 1725 mm x 725 mm and the weight of the assembly is 612.6 kg. Most of the system components are made of steel to match the thermal expansion coefficient (CTE) of the table structure of NFIRAOS, which is also made of steel.

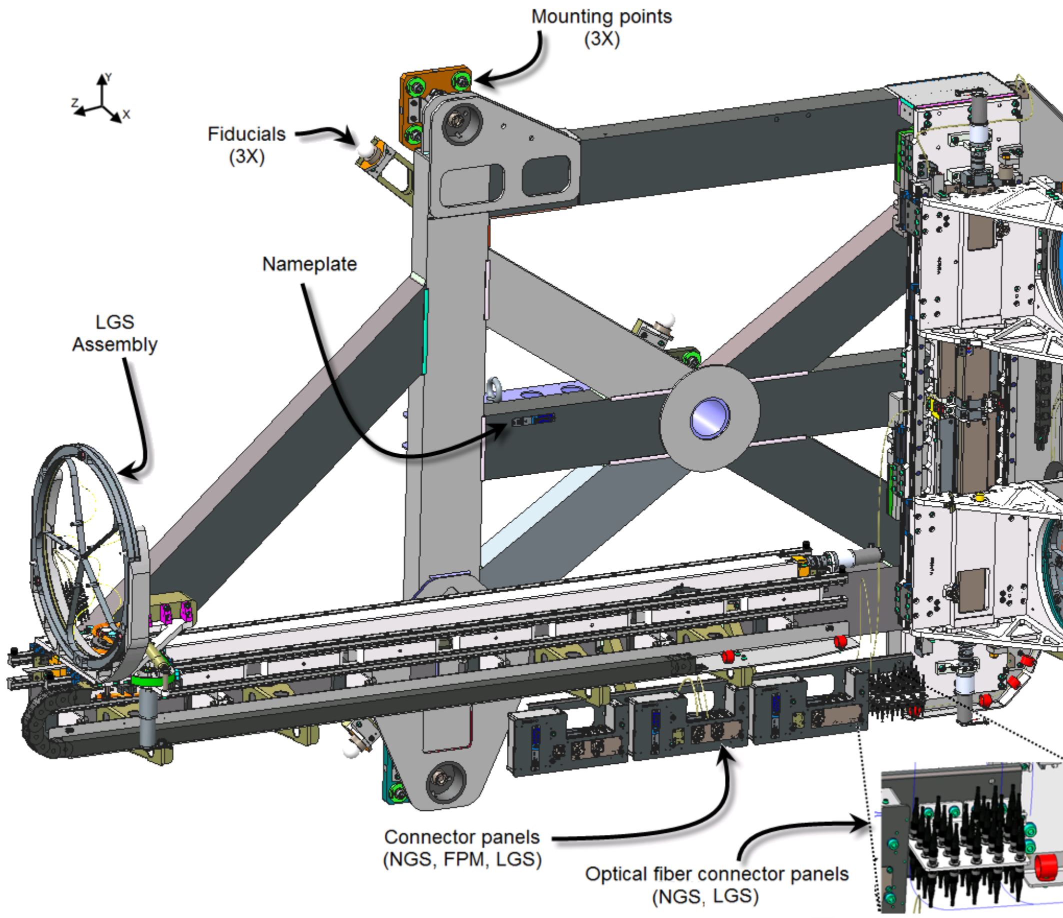

Figure 2. NSS subsystem.

2.1 Focal Plane Mask

The focal plane mask is an optical part positioned at the focal plane of NFIRAOS and works in conjunction with the NFIRAOS Science Calibration Unit (NSCU) in order to calibrate the science instruments field of view. The FPM is a pinhole mask made of ULE having a diameter of 285 mm. The FPM subassembly includes the FPM optic, the X-stage, and the Y-stage. The X&Y-stage acts as dithering stage and Y-stage is also used for deployment mechanism. The X&Y dithering of the FPM pinholes grid is required for astrometric calibration.

The FPM is mounted into a cell in an athermal way to minimize the stress in the substrate and to ensure a good positioning stability of the pinholes over the operational temperature range. The FPM is bonded in a stainless steel 17-4 PH cell using 20 equidistant dots of room temperature vulcanizing (RTV) adhesive. The adhesive is designed for low outgassing applications under extreme conditions and keeps its flexibility down to -115°C. The dot dimensions are Ø 11 mm x 1.6 mm thick. The adhesive is injected through radial holes located around the FPM cell. The thickness of the RTV has been sized to compensate the CTE mismatch between the cell and the FPM substrate made of ULE.

The X dithering adjustment is done with an off-the-shelf motorized actuator P/N M-235.2DG from PI. Flexures are used for guiding the motion. Flexure design is shown in Figure 3. They consist in eight pairs of double flexure thin blades assembly of 0.25 mm thick. The advantage of using double thin blade instead of one thicker is that it allows a longer usable axial travel for the same transversal stiffness. The flexures material is stainless steel 17-4 PH. The stage travel is ±2 mm and bumpers are located at ±3 mm (at 3 mm travel). A lever mechanism using a C-flex pivot and roller joints is used to link the linear actuator to the guiding stage. A returning spring is used on the X-stage to remove backlash movement of the stage with respect to the actuator tip. The Y dithering adjustment is given for free by the vertical rail, as it is properly designed for accurate motion.

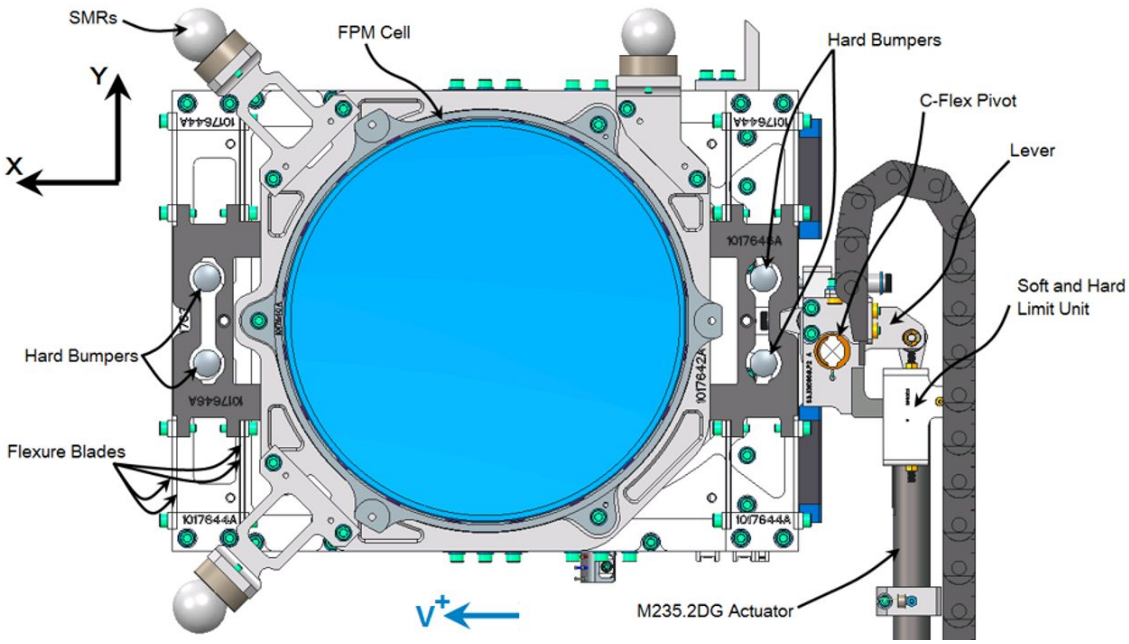

Figure 3. FPM assembly.

The deployment linear stage shown in Figure 4 is shared between FPM and NGS stages. Two sets of two rails are used to create the FPM/NGS stage: primary rails and secondary rails. They are mounted in a symmetric configuration, with 1018 steel plates in the middle to connect them. This configuration avoids undesirable bi-metallic bending of the rail assembly due to CTE mismatch between the 1050 mm long rail made of hardened steel and the 1018 steel middle plate. The CTE mismatch has been evaluated to 0.8 ppm/°C maximum. Flexural links have been added to the steel middle plate to absorb the thermal strain along the rail under temperature change.

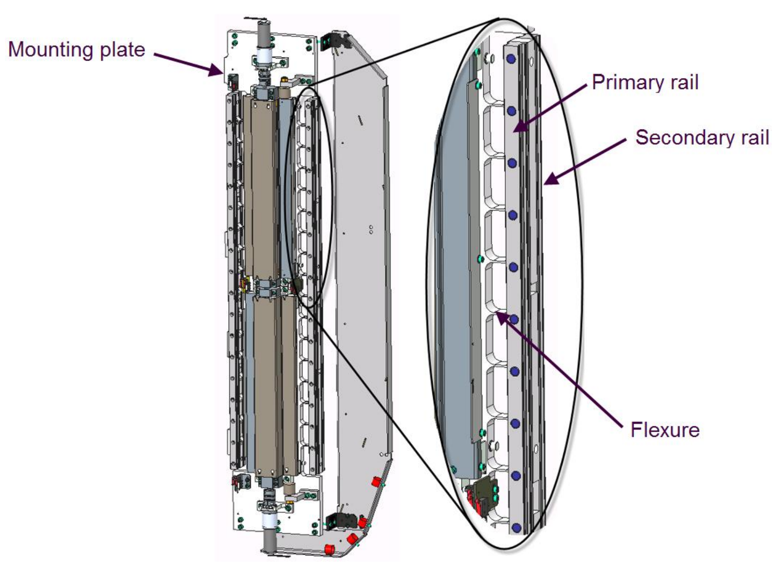

Figure 4. FPM/NGS Y-stage.

2.2 Natural Guide Star Source

The NGS is composed of 16 point sources with an apparent diameter smaller than the limit of diffraction, and one source with the same apparent diameter as the seeing (0.4 arcsec). At the focal plane, the diffraction limited point sources are achieved by shining light exiting an optical fiber through a 10 µm diameter hole. Diffraction at the apertures will produce spherical waves and the emission angle will be limited by conical baffles. The seeing-limited source will be produced by light exiting a large core multimode fiber that gets collimated by a lens, then through a 1 mm diameter aperture to limit the source angular spread. The 1 mm aperture will thus emit light with the correct apparent diameter, with uniform intensity over the whole diameter.

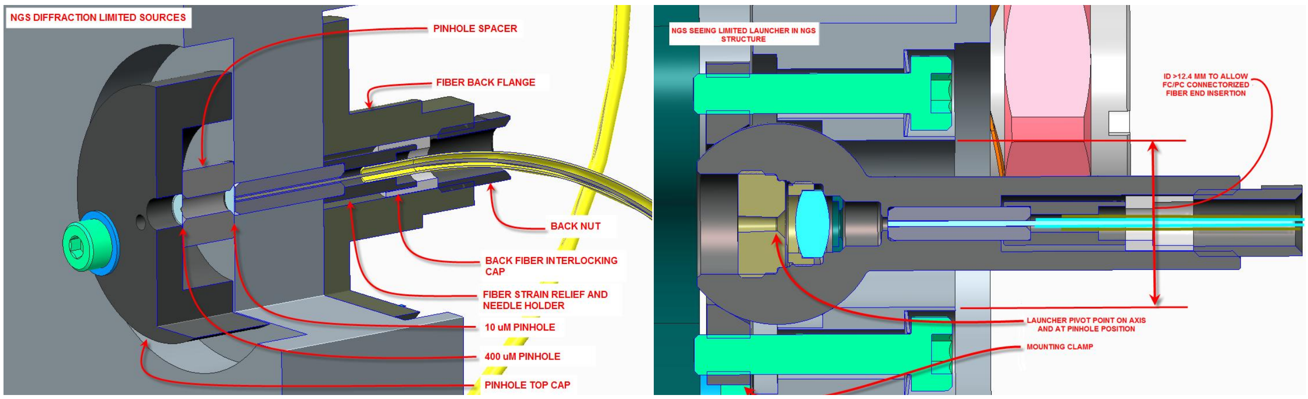

Figure 5. NGS launcher assembly. (Left) Diffraction limited source, (Right) Seeing limited source.

The NGS source fibers are mounted on a stainless steel 17-4 PH plate to match CTE with other parts in the NSS subsystem. This has the advantage to increase the positioning stability of the sources assembly relative to the NSS subsystem. Pinhole pucks are assembled on the NGS plate since 10 µm diameter holes will be difficult to machine directly on the NGS plate. Optical fibers are guided by precision holes in the mounting plate and maintained in position by a back flange. The distance between the fiber and the pinhole is kept at the minimum to reduce power loss (approximately 0.1 mm). The NGS plate provides interfaces for each sources at different levels in the optical path axis in order to create a spherical pattern for the sources. Adjustments are provided on the NGS plate to align the sources with respect to NFIRAOS optical axis. As mentioned previously, the NGS is mounted on a vertical linear stage that allows to deploy and retract the subassembly from the science optical beam.

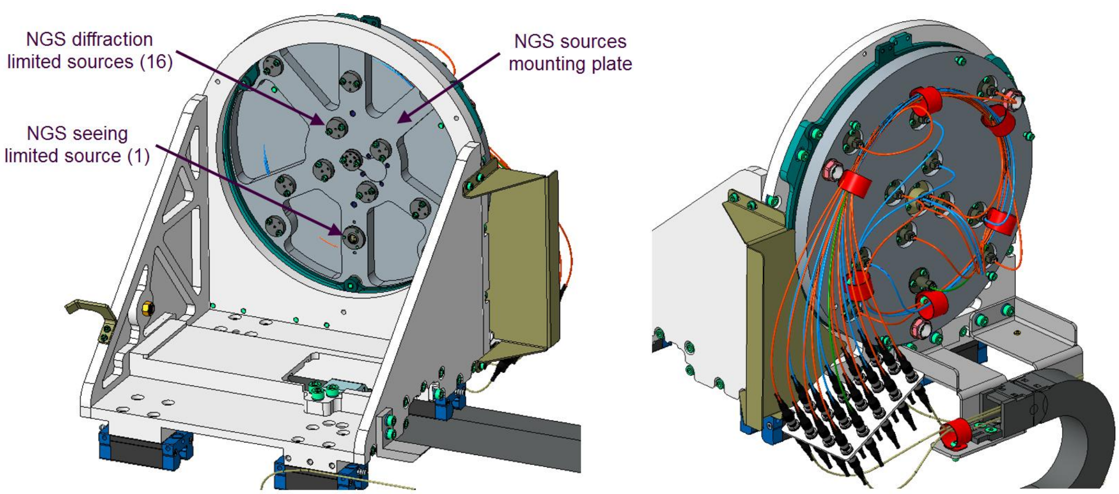

Figure 6. NGS source assembly. (Left) NGS assembly front view, (Right) NGS assembly rear view.

2.3 Laser Guide Star Source

The LGS assembly is composed of 6 sources. The design includes a spider structure that is used to hold the sources in place with a maximal dimensional stability through its operating and survival environmental conditions. The concept consists in machining the support frame of the 6 sources in a single part. This will allow to machine thin support arms to minimize the obscuration, to provide stiff support for sources and to minimize the induced stress in the spider structure that could affect the dimensional stability. Adjustments are provided on the LGS spider structure to align the sources with respect to NFIRAOS optical axis. The LGS source assembly is mounted on the flip stage that allows to remove the LGS sources from the optical path when NFIRAOS is on sky. Finally, the LGS flip stage is mounted on a custom linear stage to move the LGS source along the optical axis.

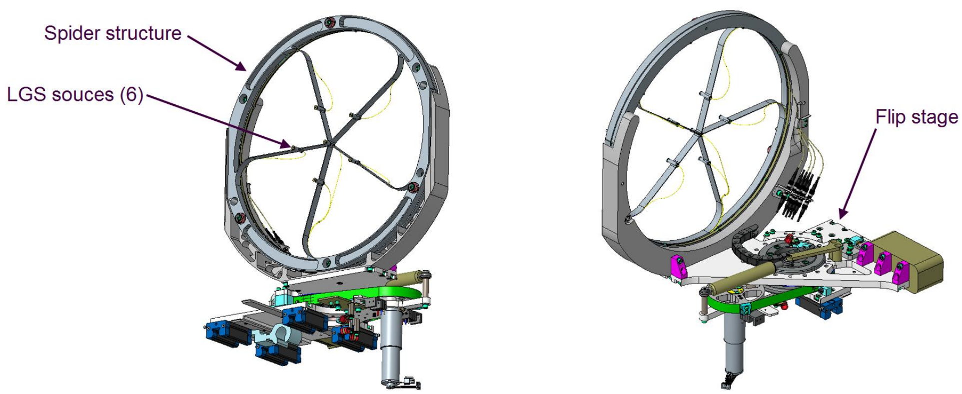

Figure 7. LGS source assembly.

The LGS linear stage provides a travel range of 1635 mm and is composed of two sets of two rails mounted in a symmetric configuration with 8 mounting plates connecting them. The primary reason for this design strategy is to create a system that is symmetric, so differences in CTE between the rail hardened bearing steel and the mild unhardened steel used for the base block will not create unwanted motions. As the temperature changes, the two sets of rails will shrink or expand equally, while the spacer blocks will move relative to each other based on the local expansion of where they are connected to the rail. The LGS linear stage is mounted on the NSS structure using 6 vertical flexures that rigidly constrains it in all degrees of freedom except axially. The flexures are used in the design to maintain rigidity while also being light and allowing for alignment. The flexure material is stainless steel 17-4 PH. To constrain the stage axially, a turnbuckle/rod-end device is used. It is ideal because it can handle a very large axial load, while being compliant in all other degrees of freedom.

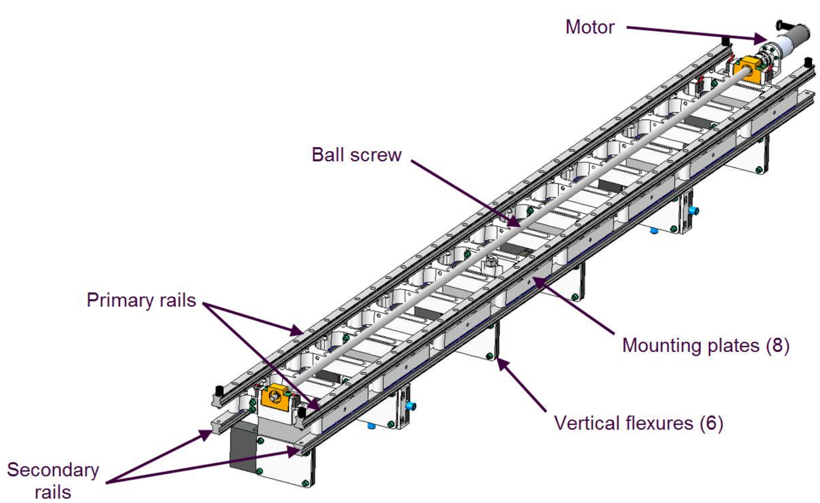

Figure 8. LGS linear stage mechanical design.

The LGS launcher optomechanical design consists in an illumination fibre, a lens, and a 1.75 mm diameter aperture stop. The lens is assembled using standard drop-in with a threaded ring. The lens barrel is used to mount the fiber ferrule and the lens. A threaded baffle is included in the lens barrel. Finally, a lock ring secures the launcher assembly into the spider structure, allowing an easy replacement of the LGS launcher if required during the lifetime of NFIRAOS.

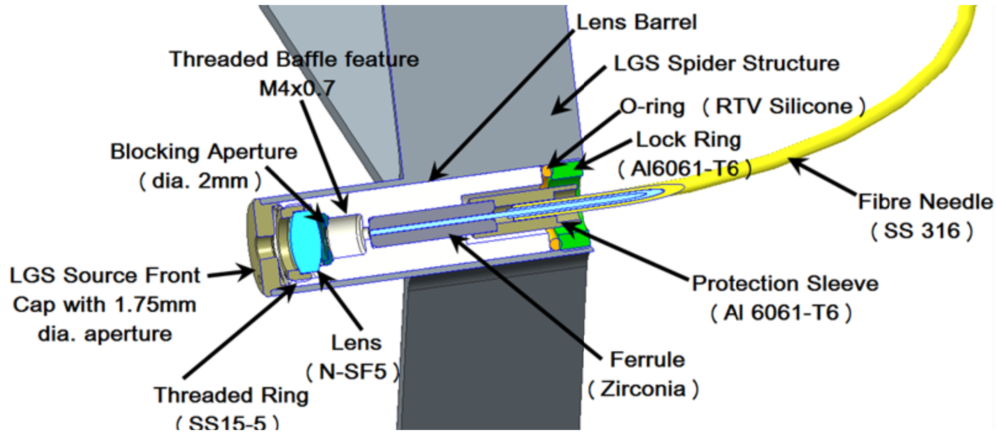

Figure 9. LGS launcher assembly.

3. NFIRAOS BEAMSPLITTERS

Figure 10 shows the science and engineering BS changer mechanism assembly. Both BS are made of fused silica, have a diameter of 500 mm, a thickness of 65 mm, and a mass of 26.0 kg. All mechanical parts of the NBS assembly are in steel to match the coefficient of thermal expansion of the table structure that is made of steel. RTV adhesive is used to bond each BS in their cells. The high CTE of the RTV allows to athermalize the fused silica BS in the steel cell. This simple design strategy has the advantage to avoid the use of invar and flexures, which would increase the cost and the risk to affect the dimensional stability by adding interfaces. The BS cells are mounted on tip/tilt mechanisms that are used for alignment. The BS tip/tilt mechanism assemblies are then mounted on a main housing, which is mounted on a rotation stage that allows selection between both BS. Finally, the rotation stage is mounted on an interface plate that enables precision positioning of the subsystem on the table structure of NFIRAOS.

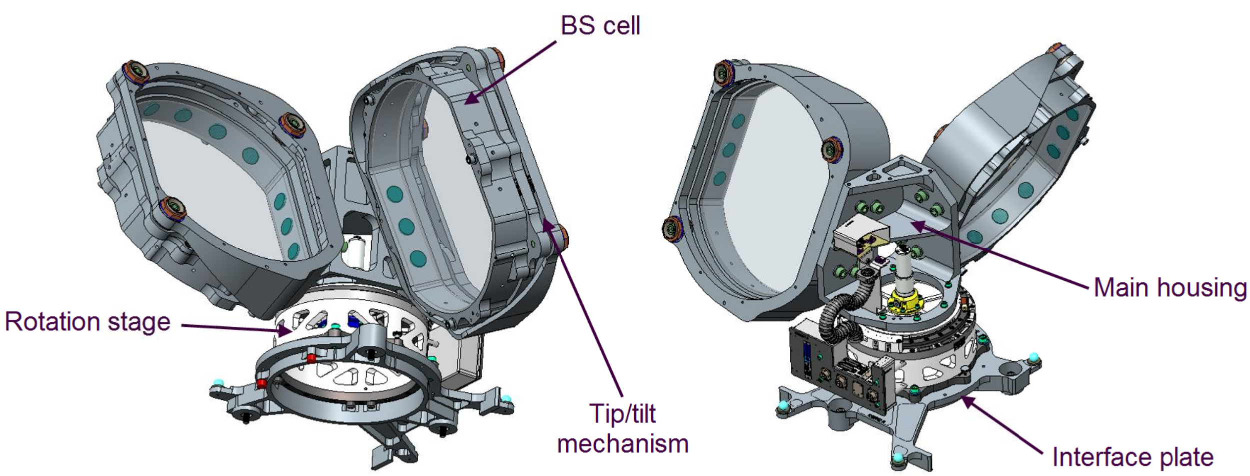

Figure 10. Science & engineering beamsplitter changer mechanism assembly.

In order to meet all the operational and survival requirements, a custom rotary stage was designed for both the NBS and the ISM mechanisms. The main components of the rotary actuator are: a bearing, motor, gearhead, coupler, reducer, and encoder. Each component complies with the -30°C minimum temperature requirement. Figure 11 gives an overview of the rotation stage design.

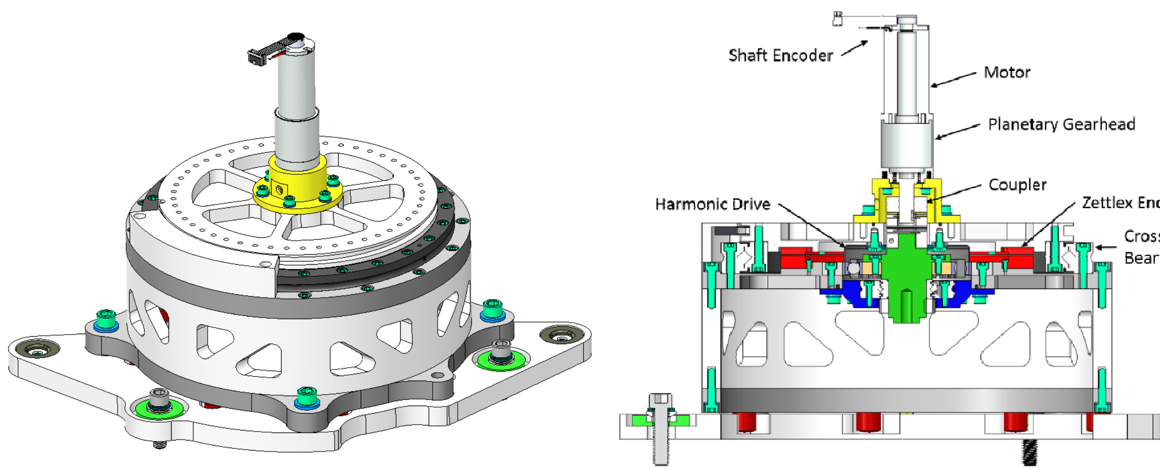

Figure 11. NBS and ISM rotation stage.

Figure 12 shows the visible light BS assembly. The visible light BS is also made of fused silica, has a diameter of 530 mm, a thickness of 65 mm, and a mass of 30.5 kg. Similarly to the science and engineering BS, the assembly is composed of a steel beam splitter cell, a tip/tilt mechanism and an interface plate. Lapped pads are used at each interface.

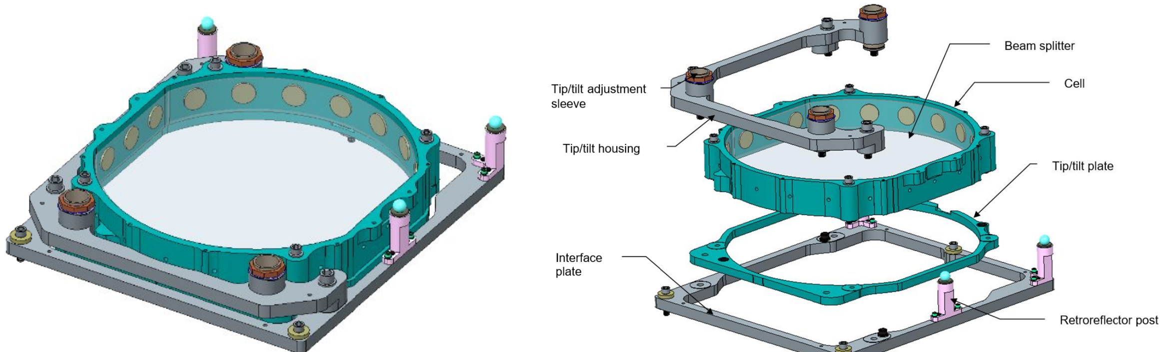

Figure 12. Visible beamsplitter assembly.

Finite element simulations have been performed to validate the wavefront error requirements under environmental constraints (transmitted and reflected WFE 18 nm RMS after focus and astigmatism subtraction) for the three different BS [2]. Temperature variation from ambient to -30°C and gravity load applied at 25 degrees as per operating orientation has been simulated. Simulation results from Ansys have been exported to SigFit software from Sigmadyne to compute the surface form deviation in order to verify the compliance with the reflected and the transmitted wavefront error requirements. Finite element analyses were also performed to verify that the optomechanical design is compliant with seismic, handling and shipping loads. Stress in the steel mechanical parts, in the BS glass, and in the RTV adhesive have been computed for each requirement of acceleration load. These analyses have shown compliance to all requirements.

4. NFIRAOS INSTRUMENT SELECTION MIRROR

The ISM mirror is made of fused silica, has a diameter of 660 mm, a thickness of 80 mm, and a mass of 49.5 kg. The ISM is mounted on a custom rotation mechanism (same as for NBS) that allows to selectively steers the light to three instrument ports. The ISM also has a tilt adjustment orthogonal to the rotation axis for alignment purposes.

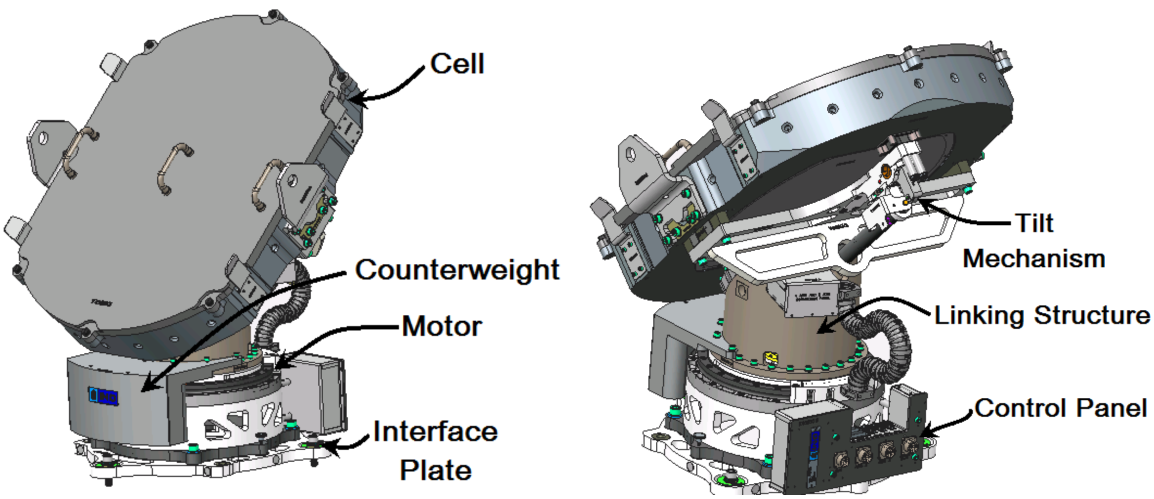

Figure 13. Instrument selection mirror. (Left) ISM assembly front view, (Right) ISM assembly rear view.

As for the NBS, the ISM mirror is bonded to its cell using silicone RTV elastomer adhesive. The thickness of the bonded joint is optimized to compensate for the differential CTE between the fused silica mirror and the steel cell. Injection holes located around the periphery of the cell are used to inject the silicone RTV adhesive between the ISM mirror and the cell. Tilting the cell is achieved by the use of two flex pivots sized for an infinite life inserted on each sides of the mirror cell. Some adhesive dots were excluded in order to prevent any distortion coming from the flex pivot support while the ISM is facing at the side port. Flex pivots are superior to bearings since they have no backlash (play), no lubrication problems, are simple to mount, and have a very low minimum operating temperature. The tilt axis created by the flex pivots is designed to pass through the center of gravity of the entire cell. The tilt motion is done with the same actuator from PI used for the FPM.

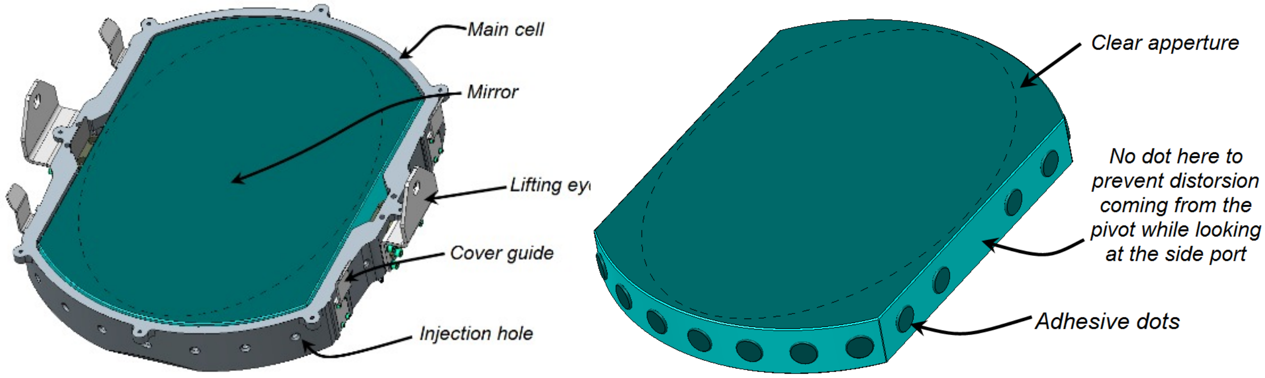

Figure 14. ISM mounting. (Left) ISM mounted in the cell, (Right) ISM adhesive dots.

Finite element simulations similar to those conducted for the NBS have been performed to validate the compliance with the wavefront error requirements under environmental constraints (reflected WFE 10 nm RMS after focus and astigmatism subtraction) as well as compliance with seismic, handling and shipping loads. Once again, simulations results have shown all requirements are met by design.

5. CONCLUSION

The optomechanical detailed design of several NFIRAOS subsystems performed at INO has been presented. These subsystems include the instrument selection mirror (ISM), the beamsplitters (NBS), and the source simulator system (NSS) comprising the focal plane mask (FPM), the laser guide star (LGS), and natural guide star (NGS) sources. Design approach to meet optical, thermal, vibrational, handling, shipping and seismic requirements compliance have been discussed. Optomechanical mounting strategy of each critical optical components are also presented. The detailed design phase being completed for these subsystems, the next step will be the manufacturing which is expected to begin in 12 to 18 months.

References

[1] Herriot, G. et al, "NFIRAOS: first facility AO system for the Thirty Meter Telescope," Proc. SPIE 9148, (2014).
[2] Lamontagne, F. et al., "NFIRAOS beamsplitters subsystems optomechanical design," Proc. SPIE 9912, (2016).