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TMT NFIRAOS - adaptive optics for the Thirty Meter Telescope

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ABSTRACT

NFIRAOS is the first-light adaptive optics system planned for the Thirty Meter Telescope, and is being designed at the National Research Council of Canada's Herzberg Institute of Astrophysics. NFIRAOS is a laser guide star multi-conjugate adaptive optics system – a practical approach to providing diffraction limited image quality in the NIR over a 30" field of view, with high sky coverage. This will enable a wide range of TMT science that depends upon the large corrected field of view and high precision astrometry and photometry. We review recent progress developing the design and conducting performance estimates for NFIRAOS.

Keywords: TMT, NFIRAOS, Adaptive Optics

1. INTRODUCTION

NFIRAOS, (Narrow Field InfraRed Adaptive Optics System), will be the first-light adaptive optics system on the Thirty Meter Telescope[1]. NFIRAOS is currently under design at the Herzberg Institute of Astrophysics of the National Research Council of Canada. It will stand on one of the two Nasmyth platforms of TMT, and be fed by the articulated tertiary mirror (M3) located in the centre of the primary mirror. The corrected beam from NFIRAOS will be sent to three client instruments, represented by cylinders on the top bottom and side of Figure 1. The electronics cabinet is shown beside the human figure on the Nasmyth platform. In front of NFIRAOS at its upper corner in this view, is a science calibration unit (NSCU) that sends wavelength and flat field calibration sources through NFIRAOS to client instruments. When observing, the beam from the telescope passes through the NSCU and enters NFIRAOS. During commission and early operations, there will be an acquisition camera on a side port, which will be replaced by an instrument eventually.

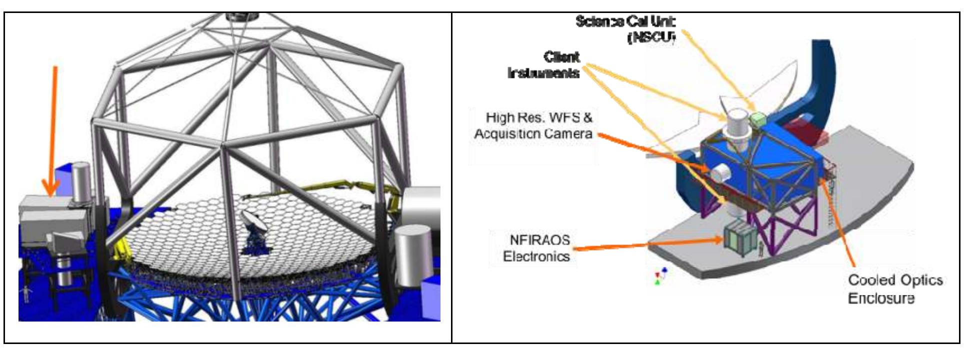

Figure 1. Left: NFIRAOS on TMT. Right: NFIRAOS on Nasmyth platform with instruments.

NFIRAOS is a Multiconjugate Adaptive Optics System with two deformable mirrors and six laser[2] guide star wavefront sensors. NFIRAOS is contained in a large 8 x 10 x 5 m (L x W x H) enclosure standing on a Nasmyth Platform, and feeds three client instruments[3] operating over 0.8 – 2.5 µm wavelength range. NFIRAOS will have high throughput and low thermal background – it will be cooled to -30 °C. Instruments provide their own rotator and interface to NFIRAOS, including a rotating seal. For wavelength and flat field calibration of client instruments, a NFIRAOS Science Calibration Unit (NSCU) feeds light in the entrance window, through NFIRAOS, to instruments. To control image distortion and tip/tilt/focus, NFIRAOS' client instruments have three low-order wavefront sensors sensing near-infrared natural guide

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stars. Inside NFIRAOS are deployable light sources simulating natural and laser guide stars, a focal plane mask with pinholes illuminated by the NSCU, as well as a turbulence phase-screen. In this paper we discuss: NFIRAOS' requirements and architecture; changes to NFIRAOS since the last SPIE conference; interior details of NFIRAOS; interfaces to instruments; integration and verification plans.

1.1 Top Level Requirements

The requirements for NFIRAOS flow down from the science requirements for TMT. Critical specifications include:

- Throughput: >80%, 0.8 to 2.5 μm
- Background Thermal Emission: < 15 % of sky and telescope
- Wavefront Error: 187 nm RMS on-axis, and 191 nm RMS on a 17" field of view
- Sky coverage: 50 % at the Galactic pole
- Differential photometry 2% for a 2 minute exposure on a 30" field of view at $\lambda = 1$ μm
- Differential Astrometry: 50 mas for a 100 s exposure on a 30" field of view in the H band
- Available from standby: <10 minutes
- Acquire a new field: < 5 minutes
- Downtime: < 1 per cent unscheduled

2. NFIRAOS ARCHITECTURE

We have selected a Multi-conjugate architecture in order to achieve the above specifications. NFIRAOS has two deformable mirrors. DM0 conjugate to the ground has 63x63 actuators, and is mounted on a tip/tilt stage. DM11 has 76x76 actuators and is conjugate to 11.2 km. This design creates a corrected field of view that is wide and relatively uniform, which benefits sky coverage (the probability of achieving the required image quality), as well as astrometry and photometry. To control the two DMs, NFIRAOS uses atmospheric tomography with six laser guide stars. These are in an asterism with five beacons in a pentagon of 70 arcseconds circumscribed diameter, plus a sixth in the centre, on-axis. The laser wavefront sensors will have polar coordinate CCD detectors, with 204792 pixels measuring 5792 gradients per WFS. Near to the centre of the pupil, 6x6 islands of 0.5 arcsecond pixels digitize the Shack-Hartmann spots, and at the edge of the pupil, these islands increase in size to 6x15 pixels, oriented radially along the elongated spots. NFIRAOS' real time controller[9] processes 1.23 mega-pixels from the LGS wavefront sensors into ~35,000 gradients and solves the tomography problem to control ~7000 DM actuators at 800 Hz.

3. OPTICAL PATH

To achieve the high throughput, there are a minimum number of optical surfaces: seven reflections plus a beamsplitter and a window. Together with cooling the system to -30°C, this optical design minimizes thermal background. Figure 2 shows an isometric view of the optical path for science light. All of these science path optics lie in an horizontal plane. Light from TMT enters through an evacuated double-paned entrance window, shown at the top and traverses a pair of off-axis paraboloid relays, each with a DM, and then reaches an instrument selection mirror that sends the light up, down or sideways to instruments.

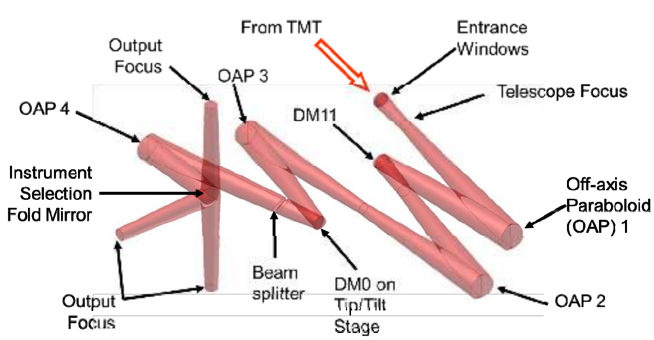

Figure 2. Isometric view of science optical path.

The pair of OAP relays in series delivers a nearly undistorted image (field distortion < 0.002% over the two arcminute field. The beamsplitter is in collimated space. It reflects light shortward of 0.8 microns wavelength towards the wavefront sensors (not shown in Figure 2.)

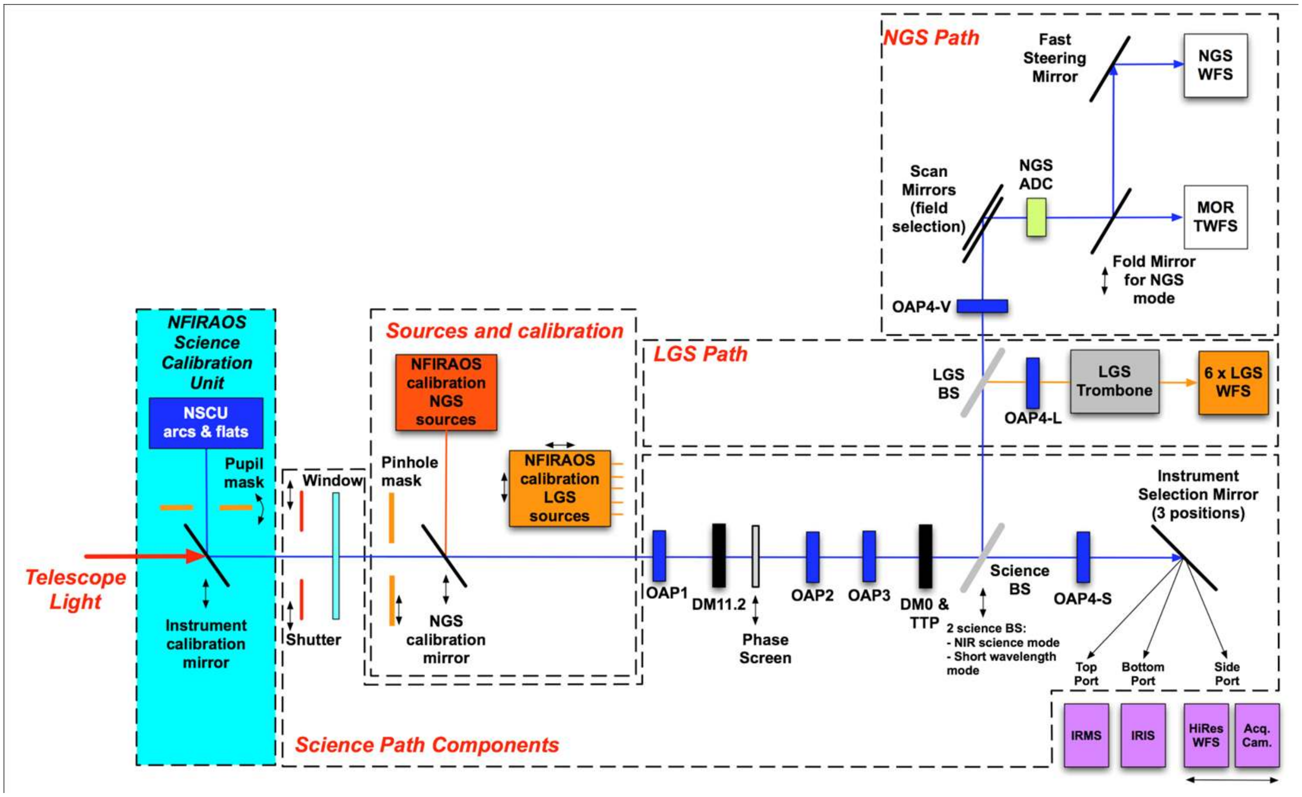

Figure 3. Block diagram of NFIRAOS optics.

Figure 3, shows a schematic block diagram of all the optics in NFIRAOS. The horizontal blue line running from left to right near the bottom of the figure depicts the science path described above. You can see the light arriving from the telescope on the left. It passes through the NFIRAOS Science Calibration Unit (NSCU). In daytime this box deploys a fold mirror into the beam for calibration of wavelength and flat field in instruments. It projects into NFIRAOS an image of a rotating pupil mask to simulate the TMT pupil. The light passing through the NSCU and enters NFIRAOS itself via a shutter and a pair of windows with a vacuum between them.

Inside NFIRAOS, the beam traverses a region with a variety of deployable calibration sources and equipment. The first is a pinhole mask at the focal plane, illuminated by the NSCU for calibrating pointing models and field distortion. Alternatively, an NGS calibration mirror can be deployed to direct an array of adjustable-brightness simulated sources for natural guide stars. Next, there is an asterism of laser guide star sources that is deployable and translates along the beam to represent varying range distance to the sodium layer.

Along the blue line representing the science path, you can see the two OAP relays, formed by OAP1, OAP2, OAP3 and OAP4-s. The relays include the two DMs and a deployable turbulence phase screen and beamsplitter on a changer. The science infrared light transmitted through the beamsplitter is directed to the three client instruments. During early operations, one instrument position will hold a patrolling diagnostic high-resolution WFS and an acquisition camera.

Turning next to the visible light reflected upwards from the beamsplitter, you see the laser light is diverted to the right and is reimaged by OAP4-L, with the same prescription as the final science OAP. Then a trombone refocuses the laser light as the sodium range distance changes with telescope zenith angle, and with variations in the height of the sodium layer. Six individual pickoff mirrors direct the light to collimators and LGS WFSs.

The natural visible light continues upward in the diagram, to a pair of scanning mirrors that select an individual star, send its light through an atmospheric dispersion compensator (ADC) and (when using lasers) into moderate order (12x12) radially symmetric mode sensing truth wavefront sensor (MOR TWFS). This WFS measures errors originating from the laser WFSs and is processed to update the reference vectors for the LGS WFS.

NFIRAOS can also operate in classic NGS AO mode by deploying a fold mirror to send the visible light towards a 60x60 NGS WFS. A fast steering mirror in this path dithers the beam to calibrate centroid gain of the NGS WFS in real time, to compensate seeing variations.

4. MECHANICS AND OPTICS

Following the previous edition of this conference in 2010 we have made substantial improvements and cost savings to the design of NFIRAOS. The four-OAP design dramatically reduced image distortion, and especially improved the aberrations in the laser beacons at finite range. Incorporating this optical design increased the size of NFIRAOS about 2x, but the larger volume permits simplifications and savings. NFIRAOS now uses a space frame design for optics support, which is stiffer and improves access to components. There is a simplified turbulence simulator (simply a phase screen in collimated space, instead of a telescope simulator in front of NFIRAOS). The laser guide star wavefront sensor subsystem uses a simple trombone, thereby removing 20 motors from NFIRAOS. Rather than using very expensive super-insulation we now intercept heat leakage with a buried cold plate within the enclosure walls. Moving the acquisition camera to a side port meant that the instrument selection fold mirror can now be a single-axis device. The acquisition camera now patrols the output field, reducing its instantaneous field of view and cost. The optical source simulators are simple pinholes deployed into the beam, without any auxiliary optics. There is now only a single Truth WFS, where previously we had a very high order WFS, now replace by the exterior calibration WFS. This sensor on a side port will be replaced by a third instrument later.

Figure 5 shows the opto-mechanics supported by a truss space-frame. In this view, the entrance window is on the left and the laser WFS trombone is on the right. The curving thick purple object on the lower right is the wiring for DM0. Just below this, you can see one of three bipods, which penetrate the cold enclosure and support the space frame.

All of the components are shown in the Figure 4, which is drawn from the same viewpoint as Figure 2. Again, the infrared science light path is in red, and we have added the natural visible light in green and the laser light is yellow. Near the top of this figure, you can see the frames for the source simulators and for the turbulence simulator phase screen. In the foreground is OAP-4V that reimages the NGS light, suspended below the plane of the science optics. Above that is the LGS trombone and then the VNW (Visible Natural Wavefront sensor) bench supporting the Truth Wavefront Sensor and the NGS-mode WFS.

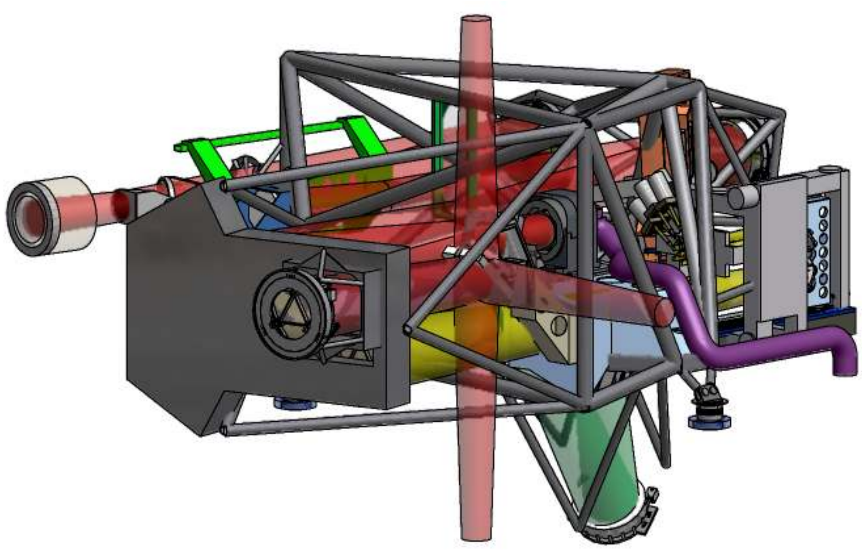

Figure 4. Isometric view of NFIRAOS optics and space frame.

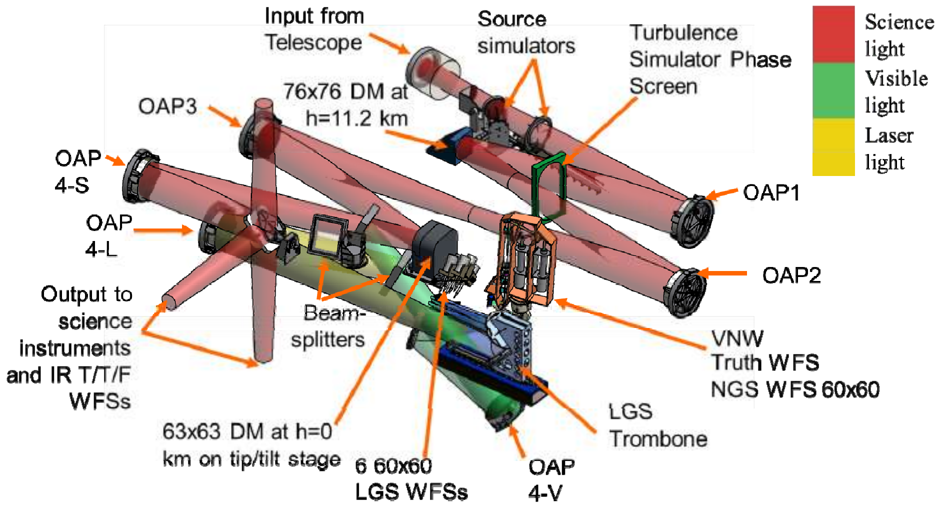

Figure 5. Isometric view of NFIRAOS optics.

5. THERMAL ENCLOSURE

NFIRAOS and its client instruments are supported by a steel exoskeleton that surrounds the cooled optical enclosure. This enclosure will be slightly pressurized to keep moisture from leaking into NFIRAOS. During initial cooling, two large air-handling units will bring NFIRAOS down to operating temperature in under 15 hours. Then these units will be switched off, and the temperature will be maintained by cold plates sandwiched into the insulated walls. These plates intercept heat from the dome, and maintain an isothermal – 30 C environment within NFIRAOS. To service NFIRAOS, it will be warmed up to dome temperature before opening.

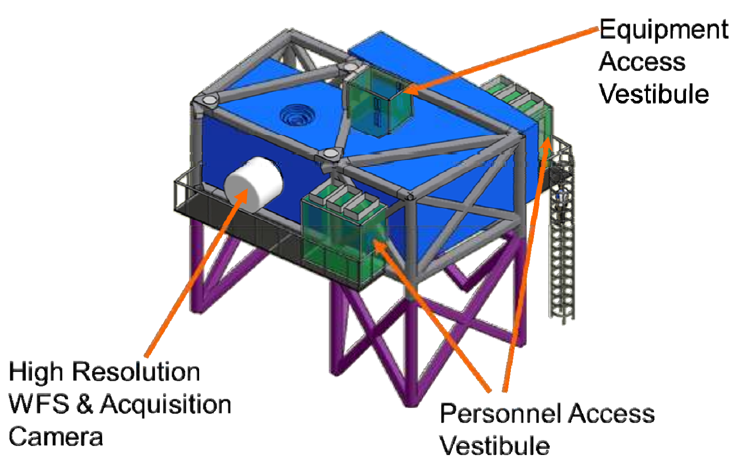

Figure 6. Isometric view of NFIRAOS optics.

Deployable personnel access vestibules will be installed over access hatches to permit people and equipment to enter NFIRAOS. These vestibules will be equipped with air knives using filtered air to reduce particulate contamination of NFIRAOS.

Gate valves inside each instrument port, together with removable insulated covers permit exchanging instruments without warming NFIRAOS. Instruments have their own rotator bearings supported by NFIRAOS exoskeleton. Each instrument supplies rotating seals that mate with the buried cold plate inside the walls of NFIRAOS and keep the cold dry air inside NFIRAOS.

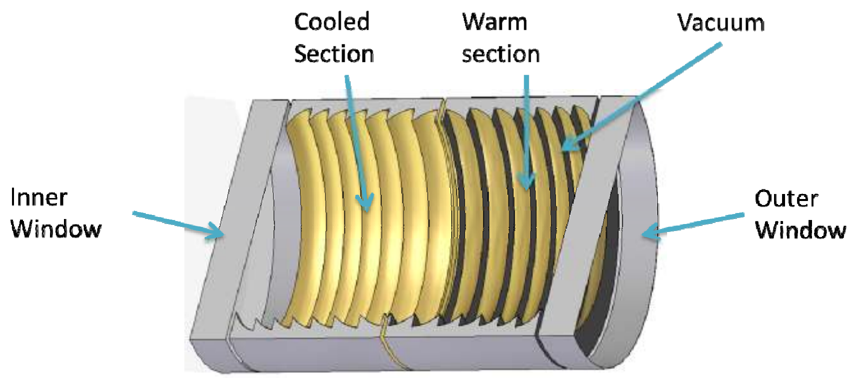

Figure 7. Windows with thermal baffle.

Computational fluid dynamics (CFD) modeling of heat transfer through and at the windows showed that that radiation from the outer window would warm the inner window, and sub-cool the outer window, and cause ‘window seeing’ or turbulence caused by convection on the window surfaces. We contracted Space Dynamics Laboratory to design a thermal baffle for NFIRAOS. Two 400 mm diameter fused silica windows are separated by 400 long vacuum baffle. The baffle is in two halves, with a warm section, slightly above dome temperature near the outer window, and a cold section adjacent to the inner window cooled to -43 C (the evaporation temperature of R507 refrigerant). Baffle fins are black on the side facing the nearest window, and gold facing the further window. The radiative heat transfer from the windows to the baffle nearly balances the radiative transfer directly between the windows, resulting in < 0.5 C difference between the windows surfaces exposed to the air, both inside NFIROS and facing the dome. Window seeing will be neglible.

6. HIGH CONTRAST IMAGING

NFIRAOS will be the only adaptive optics system available during early light operations of TMT. The astronomical community is very interested in using NFIRAOS in natural guide star mode (without lasers) to achieve the highest possible image quality on-axis, with the greatest possible contrast, for example, to image exo-solar planets. We have evaluated the contrast achievable with NFIRAOS to assess what high contrast astronomy is possible[8], and to identify cost-effective upgrades that might be implemented in NFIRAOS, and to ensure that the telescope itself is a good platform for high-contrast imaging. We find for example that NFIRAOS, although it is not designed as a high contrast AO system, is comparable to or better than the expected performance of GPi on the 8-m Gemini telescope, and has the advantage of permitting observing close into the parent star.

7. REAL TIME CONTROL SYSTEM

7.1 Computing

The real time computing for NFIRAOS has three major steps: measuring wavefront slopes from WFS pixels; doing atmospheric tomography (the majority of the total computation); and fitting DM commands based on the reconstructed atmospheric turbulence. Adaptive Optics Real-Time Control systems for next generation ground-based telescopes demand significantly higher processing power, memory bandwidth and I/O capacity on the hardware platform than those for existing control systems. The Dominion Radio Astrophysical Observatory, in Penticton British Columbia, also part of the National Research Council of Canada, developed an FPGA based high-performance computing platform that is very suitable for Adaptive Optics Real-Time Control systems[9]. With a maximum of 16 computing blades (‘Kermode’ boards, Figure 8), 110 TeraMAC/s processing power, 1.8Terabyte/s memory bandwidth and 19.5 Terabit/s I/O capacity, this ATCA architecture platform has enough capacity to perform pixel processing, tomographic wave-front reconstruction and deformable mirror fitting for first and second generation AO systems on 30+-meter class telescopes. As an example, they demonstrated that one computing blade can do the real time tomography for NFIRAOS in 250 microseconds. In addition to FPFGAs, we continue to assess algorithms suitable for emerging technologies like clusters and GPUs[6].

7.2 Point Spread Function Estimation

To help meet the demanding requirements for astrometry and photometry, knowledge of the delivered point spread function (PSF) throughout the field of view, will assist quantitative astronomical measurements. NFIRAOS team at NRC and at TMT are collaborating to develop point spread function estimation algorithms[7]. The intent is to process telemetry from NFIRAOS to provide PSFs for every science exposure.

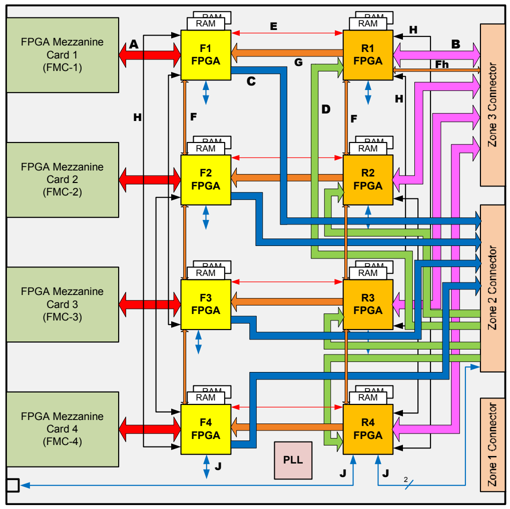

Figure 8. Real Time Computing Blade (Kermode board).

7.3 Plate Scale Control

NFIRAOS, because it is an LGS MCAO system, uses three natural guide stars WFSs in each instrument, for controlling tip, tilt and focus since LGS WFSs are blind to tip/tilt, and LGS focus measurements are corrupted by changes in the sodium altitude. As well, if the two DMs have opposing quadratic Zernike mode shapes (focus and two astigmatisms) in the correct proportions, then the LGS will be blind to them, but the delivered science beam will be magnified and also stretched asymmetrically in X versus Y – termed 'plate scale modes.' Therefore, the NGS WFSs control these plate scale modes as well. The baseline for Tip/Tilt, focus and plate scale control in NFIRAOS was until recently to use a Type II controller. Here 'II' means two integrators in series, together with a lead filter compensator for stability. Recent work[11] shows that a Kalman filter approach gives better performance for reducing those errors under the control of the NGS WFSs.

7.4 Meteor Tracking

Small meteors usually burn up near the bottom of the sodium layer. Meteor trails can lead to temporary dramatic changes in the altitude of the sodium layer. This altitude change is very rapid, typically over 1 second, and after some unpredictable period of 10-20 seconds, can transition back to the nominal mean altitude also in about 1 second. The altitude change is also very drastic and can jump by up to 1 km which, on the face of it, would cause 4 micrometers defocus errors on LGS WFS measurements for a 30-m telescope, unless properly tracked. Measurements by the UBC Lidar detected ~20 meteor trails / hour, and of these, 1-2 are significant events[12].

We built a Simulink simulation[5] for TMT NFIRAOS including: meteor events measured by the UBC Lidar, on-instrument NGS WFS focus sensing and a full trombone servo model including non-linear focus range vs stage position. We optimized our control architecture and traded off motor power dissipation versus residual wavefront error and Shack-Hartmann spot displacement and found range tracking errors induce 11 nm WFE in normal conditions and brief (1s) jumps of 30-80 nm WFE at the beginning and ending of meteor transients.

8. DM ELECTRONICS

NFIRAOS will incorporate two Deformable Mirrors[4]: DM0 with 3125 actuators in a 63x63 circular aperture and DM11 with 4548 actuators in a 76x76 circular aperture. The NFIRAOS DM actuators are piezoelectric with a capacitance of 15 nF and require a drive voltage swing of −400 V to +400 V to traverse the full rated stroke of 14 µm before flattening. For mirror safety, the amplifier output voltage slew rate must be limited below 100 kV/s, but must have a minimum rate >25 kV/s to adequately correct turbulence. The power consumption is half a watt per amplifier, while providing short circuit protection and unconditional stability. The NFIRAOS Deformable Mirror Electronics (NDME) receive Real Time Controller (RTC) command frames over multiple sFPDP fiber links and drive the output voltages to the commanded values with minimal latency, at the AO loop rate of 800 Hz. Due to the unprecedented number of actuators in the NFIRAOS DMs, no suitable drive electronics, with the needed combination of mirror- and self-protection, power consumption, slew rate, noise and stability, and self-diagnostics are currently available from commercial vendors. A new specialized electronics solution appropriate for large scale ELT AO systems is needed. In order to aid the development and procurement of such electronics for NFIRAOS, a reference design[10] is underway at the National Research Council of Canada's Herzberg Institute of Astrophysics (HIA). This will serve to lessen the procurement costs and risks by outlining the overall architecture of the system and demonstrating a fully validated, compact, 96-channel output module suitable for high order DME systems. The demonstration of the reference design will also serve to engage a competitive bid process for its fabrication. To date we tested a prototype 32 channel version with a line of actuators and met all the requirements.

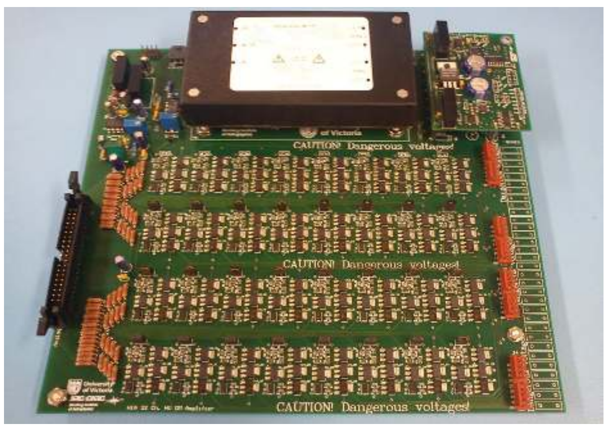

Figure 9. Real Time Computing Blade (Kermode board).

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