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Evaluating Sky Coverage for the NFIRAOS Tip/Tilt Control Architecture

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ABSTRACT

The Narrow Field Infrared Adaptive Optics System (NFIRAOS\textsuperscript{1,2}) is the first light Laser Guide Star (LGS) Multi-Conjugate Adaptive Optics (MCAO) system for TMT.\textsuperscript{3} NFIRAOS needs to correct 2-axis tip/tilt jitter disturbances, including both telescope vibration and atmospheric tip/tilt, to a residual of 2 milli-arcsecond (mas) RMS with 50\% sky coverage at the Galactic pole. NFIRAOS will utilize multiple infrared tip/tilt sensors, as sky coverage benefits greatly from wavefront sensing in the near IR where guide star densities are greater and the NFIRAOS AO system "sharpens" the guide star images. NFIRAOS will also utilize type II woofer-tweeter control to correct tip/tilt jitter. High amplitude, low bandwidth errors are corrected by a tip/tilt platform (woofer), whereas the low amplitude, high bandwidth disturbances are corrected by the deformable mirrors. A prototype development effort for the relatively large, massive DM tip/tilt stage is now underway. Detailed Monte Carlo simulations of the complete architecture indicate that the sky coverage and tip/tilt control requirement for NFIRAOS can be met, with some margin available for stronger input disturbances or shortfalls in component performance.

1. INTRODUCTION

The Narrow Field Infrared Adaptive Optics System (NFIRAOS) is the early light AO system for TMT. NFIRAOS will be a Multi-Conjugate Adaptive Optics (MCAO) system with 2 deformable mirrors (DM) controlled using 6 Laser Guide Star (LGS) and 3 tip/tilt (including a tip/tilt/focus) infrared NGS wavefront sensors.

NFIRAOS needs to correct 2-axis tip/tilt jitter to a residual of 2 milli-arcseconds (mas). The tip/tilt jitter disturbances include atmospheric turbulence and telescope vibration effects caused by wind shake and mechanical vibration. The telescope vibration has greater high frequency content and is potentially difficult to compensate. Due to optical design limitations, NFIRAOS will not have a dedicated tip/tilt mirror. Instead, one of its two deformable mirrors (DM0, conjugated to 0 km) will be mounted on a 30 cm tip/tilt platform. In order to meet the requirements, type II woofer-tweeter control is utilized to correct the tip/tilt jitter.\textsuperscript{4} High amplitude, low bandwidth errors are corrected by the tip/tilt platform (woofer), whereas the low amplitude, high bandwidth disturbance are corrected by the deformable mirror. A prototype development effort for the relatively large, massive DM tip/tilt stage is now underway at CILAS, and has passed an interim fabrication review this March. The tip/tilt stage will have a 20 Hz bandwidth (-3dB) with the \~32 kg DM0 mounted. Theoretical analysis and simulation show that a DM with a 10-12 \( \mu \)m stroke will be capable of applying the tweeter correction with effectively no additional saturation. Simulations show that woofer-tweeter control will meet the NFIRAOS requirement for tip/tilt jitter compensation, with some margin available for stronger input disturbances or shortfalls in component performance.

NFIRAOS is required to achieve this level of tip/tilt compensation with 50\% sky coverage near the galactic pole. Sky coverage refers to the cumulative probability density function (PDF) quantifying the odds of obtaining a given RMS tip/tilt jitter for a randomly selected science target. To meet this requirement, infrared (IR) tip/tilt wavefront sensing is utilized, which has two major advantages: 1) IR tip/tilt sensing increases the guide...
star density; 2) IR tip/tilt sensing improves the guide star limiting magnitude because guide star images are sharpened by the AO system.

Anisoplanatism is an additional source of tip/tilt jitter when the guide star is separated from the science target. To minimize this error, there will be 2 tip/tilt (1 subaperture) and 1 tip/tilt/focus (TTF, 2x2 subapertures) IR NGS wavefront sensors in each NFIRAOS instrument (except IRMS, which only has 1 TTF on account of its more relaxed requirement for tip/tilt control). From the sky coverage simulation results, we find that the tilt anisoplanatism modes can be adequately sensed by 3 NGS wavefront sensors, and can be adequately corrected with 2 DMs. On average, at least 3 IR guide stars of sufficient brightness for tip/tilt sensing will be available within the 2 arc-minute NFIRAOS field-of-view.

Large, low-noise, and high-speed IR detector arrays will be used in the IR wavefront sensors to enhance limiting magnitude and facilitate guide star acquisition. The electron bombard CCD (EBCCD, e.g. MOSIR 950) is an interesting option with its low read noise (<1 e), although at the cost of higher dark current and lower quantum efficiency. Sky coverage analysis shows that this EBCCD is quite competitive with the expected performance of HgCdTe detectors (e.g. “Calico Mux”).

2. TIP/TILT CONTROL ARCHITECTURE

The tip/tilt control of NFIRAOS is through a tip/tilt stage which serves as a woofer, and a deformable mirror which serves as the tweeter. In order to gain sufficient tip/tilt rejection, an additional integrator is used to control the tip/tilt stage as indicated in Figure 1, which shows the block diagram of the controller. The rejection transfer function is shown in Figure 2 for a representative control loop update rate of 80 Hz, which is about the sampling frequency for the median sky coverage.

The spectra of telescope windshake jitter are shown in Figure 3. The four curves with similar shape are from the current modeling of the telescope design, under different percentile of wind conditions. The remaining curve is from the 2006 NFIRAOS conceptual design report, at a time when these modeling results were not yet available and a more conservative estimate for telescope windshake was utilized. Figure 4 shows the residual tip/tilt jitter due to windshade after the woofer-tweeter correction by NFIRAOS for different NGS sampling frequencies. The jump near 90 Hz is due to the reduced DM tweeter gain below this sampling frequency to maintain adequate phase margin.

A prototype version of the tip/tilt stage is currently in fabrication at CILAS, with testing and delivery expected later this year.

3. SKY COVERAGE FOR NFIRAOS

3.1 The Sky Coverage Simulator

The sky coverage Monte Carlo simulator for NFIRAOS is briefly reviewed here. Figure 5 shows the block diagram of the sky coverage simulator. The guide star model, turbulence profile, telescope windshade jitter,
Figure 2. The tip/tilt rejection function with woofer only, tweeter only, and woofer/tweeter controls for a representative control loop update rate of 80 Hz.

Figure 3. The telescope wind shake power spectra from the 2006 NFIRAOS conceptual design report and from current telescope design modeling are shown. The latter are shown under different percentile of wind conditions.
Figure 4. The residual tip/tilt jitter due to windshake after the woofer/tweeter control, as a function of WFS sampling frequency. The input tip/tilt power spectra is show in Figure 3.

Figure 5. The sky coverage simulator block diagram.

and AO system parameters are specified as inputs, and a random guide star field is generated based upon the guide star model. All possible combinations of tip/tilt and tip/tilt/focus guide stars are enumerated. For each combination, an iterative process is carried out to optimize the control bandwidth and minimize the tip/tilt wavefront error (WFE). The residual error is computed including telescope windshake, WFS measurement noise, tilt anisoplanatism, and time delay effects.

The combination of guide stars and control bandwidth that has the best performance will be selected and assigned as the tip/tilt performance for this guide star field. The same step is repeated for a number of random guide star fields. Finally, the tip/tilt performance of all the guide star fields are sorted to generate the PDF.

3.2 Sky Coverage Variations Across TMT Candidate Sites

Sky coverage values for three TMT candidate sites, using the updated wind shake model from the telescope design (Figure 3) and an updated estimate of the end-to-end optical transmittance of ~0.51, are shown here. We have also upgraded our guide star model to the Besancon catalogue. Standard HgCdTe IR detector parameters were considered, with a quantum efficiency of 0.5 and 5 e of read out noise (RoN). Figure 6 shows the turbulence profiles used for the different sites under median seeing conditions (obtained by the TMT site testing program). Figure 7 shows the guide star “sharpening” effect in J band as a function of the angular distance from the center.
Figure 6. Turbulence profile measurements (from MASS instrument) of three TMT candidate sites are shown along with the TMT SRD profile.

Figure 7. The sharpening effect in J band from MCAO compensation.

The sky coverage is greatly influenced by this “sharpening” effect. Table 1 shows a comparison of the rms tip/tilt jitter (averaged over the 10" field of view of the IRIS client instrument) for these sites referenced against Armazones under median seeing conditions, for 50% and 70% percentile telescope wind shake. The errors are expressed as equivalent high order wavefront errors in nm. Figure 8 plots the cumulative probability density function of sky coverage for site Armazones, for both HgCdTe and EBCCD detector options (see Section 3.3).
Figure 8. The cumulative probability density function of sky coverage at the Armazones site, for EBCCD and HgCdTe detector parameters with different values for dark current or read out noise.

<table>
<thead>
<tr>
<th>Site</th>
<th>TT WFE (nm)</th>
<th>50% Wind Shake</th>
<th>75% Wind Shake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armazones</td>
<td>48.1</td>
<td>52.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Comparison of the tip/tilt jitter. Armazones is expressed as the baseline, and other three sites are expressed in incremental WFE in quadrature. The negative sign in front of the numbers means the site is better than the baseline. An rms WFE of 36 [51] nm corresponds to an rms tip/tilt jitter of 1 mas in one [both] axes.
3.3 Sky Coverage with New Detector Options

The electron bombard CCD (EBCCD) has become more interesting as an option for NFIRAOS IR NGS WFS detector, due to its low read noise (<1 e) and readily available technology*. The dark current of the EBCCD (MOSIR950) is rated at 400[20]e/s when cooled to -35[-55]°C, which is equivalent to $\sim \sqrt{400[20]/80} = 2.23[0.5]e$ at NFIRAOS NGS average sampling frequency of $\sim 80$ Hz (based upon sky coverage analysis). The quantum efficiency of the EBCCD is $\sim 0.3$, significantly lower than the value of 0.5 – 0.7 for a conventional IR HgCdTe detector. There is also an excess noise factor of 1.1 which degrades the S/N ratio. Despite this, the EBCCD is still quite competitive with the HgCdTe option. Figure 9 plots a comparison of the median sky coverage for the EBCCD and HgCdTe detectors under 75 percentile wind shake conditions for the Armazones and Mauna Kea sites. We can see that the EBCCD, when cooled to -35[-50]°C, is comparable to HgCdTe with $\sim 8[4]e$ read out noise. The cumulative PDF in Figure 8 confirms this observation.

4. FUTURE WORK

A higher fidelity sky coverage simulator is in the plan, based upon physical optics modeling of the complete order 60x60, LGS MCAO control system for NFIRAOS. It will utilize the “split tomography” control architecture to effectively decouple the LGS and NGS control loops. We will run an LGS MCAO simulation with idealized control of the tip/tilt and tilt anisoplanatism modes and collect point spread function (PSF) time histories for (at least) several hundred NGS across the NFIRAOS field of view. Monte Carlo simulations of the NGS loop will then be carried out in post-processing in a similar way as the current sky coverage simulator, emphasizing the difference in tip/tilt performance for a given combination of tip/tilt(/focus) stars.

This simulator will model full-order, zonal control of LGS loop. It will feature physical optics modeling of each tip/tilt(/focus) NGS WFS that takes into account the TMT pupil function, spatial aliasing of higher-order wavefront modes and speckle noise, WFS detector characteristics, the WFS frame rate, and matched filter gradient estimation. It will be capable of modeling J+H band wavefront sensing, which is expected to increase the sky coverage, particularly with poor seeing and/or a small isoplanatic angle.

*Although the current commercial version of this detector is restricted to video frame rates, higher frame rates would be possible with an upgraded detector controller.
Sky coverage estimates that account for NGS pick-off arm patrol field limitations and pupil vignetting also need to be developed, as well as performance estimates for different telescope zenith angles. Other planned future work is to determine performance for specific interesting deep fields, e.g., Hubble deep field (HDF), HDF south, and UHDF, etc.

Following the fabrication of the tip/tilt stage prototype by CILAS, there will be testings of its performance.

5. CONCLUSION

We have reviewed the tip/tilt control architecture of NFIRAOS and noted the status of prototyping of the tip/tilt stage. The sky coverage simulator was briefly reviewed, and a planned upgrade of the simulator was discussed. Finally, we have shown that the sky coverage requirements for NFIRAOS can be met with margin, thanks to the selected tip/tilt control architecture and recent updates to the telescope modeling.

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