Predicted Sky Coverage of NFIRAOS on TMT

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Abstract. TMT has chosen the MCAO system NFIRAOS to be its first light AO system in part to provide astronomers with exceptional sky coverage. The TMT science requirements demand that its AO system provide wavefront errors of less than or equal to 191 nm at the galactic pole at least 50% of the time (under median atmospheric conditions when observing at zenith). This requirement drove many aspects of the NFIRAOS design from the size of the FOV, to the use of NIR MCAO-corrected NGSs, to the sensitivity of the WFSs (and corresponding limiting magnitude of the NGSs). In this paper, we build upon the sky coverage simulations of L. Wang et al. to produce smooth sky coverage maps generated for different hour angles (potential exposure time lengths), and different atmospheric conditions. We show that NFIRAOS should meet its sky coverage requirement at the North Galactic Pole, and that the sky coverage generally will be much higher than 50% at lower galactic latitudes.

1. Introduction

Historically, AO systems have had very low sky coverage. Single conjugate Natural Guide Star (NGS) AO systems require a bright NGS within approximately 10 arcseconds of the target. In practical terms, this limited the use of AO systems to targets that could serve as their own NGS. The advent of Laser Guide Stars (LGSs) has improved sky coverage, but a tip-tilt NGS is still required within 30 arcseconds of the target. LGS AO systems deliver a sky coverage of less than 10% for galactic latitudes greater than 60 degrees [1] (where the stellar density drops significantly from the plane of the galaxy). One reason Multi-Conjugate AO (MCAO) systems are interesting (beyond the obviously larger corrected field of view) is that the sky coverage should be significantly higher.

NFIRAOS, the facility MCAO system being designed for TMT [2], was envisioned to deliver excellent performance over a large fraction of the sky. This qualitative vision has been translated into a sky coverage requirement: NFIRAOS is required to deliver a wavefront with an RMS wavefront error (WFE) of less than 191 nm and less than 2 mas of residual tip/tilt jitter under median atmospheric conditions for a zenith angle of zero at the Galactic Pole 50% of the time. The phrase, “at the Galactic Pole 50% of the time,” means that the WFE

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requirement must be met for 50% of random asterisms drawn from a distribution with the cumulative stellar distribution function of the (North) Galactic Pole.

A number of NFIRAOS design choices have been driven by this sky coverage requirement. The NFIRAOS client instruments will employ 3 On-Instrument Wavefront Sensors (OIWFSs). Two will be tip-tilt WFSs and the third will be a tip-tilt-focus sensor needed to track focus as the altitude of the sodium layer varies. These OIWFSs will incorporate NIR detectors so that they can benefit from point spread function (PSF) cores imaged at the TMT diffraction-limit, as delivered by NFIRAOS. By taking advantage of this guide star sharpening, NFIRAOS can use NGSs as faint as J=22 magnitudes. The OIWFSs will be pick off any star within the 2 arcminute field of regard of NFIRAOS, although the guide star sharpening decreases outside of 35 arcseconds (the radius of the LGS asterism).

NFIRAOS meets its sky coverage requirements, and in this proceeding we show how we expect NFIRAOS to perform over the observable sky. A more detailed treatment can be found here [3]. In section 2, we describe the methods used to create all-sky sky coverage maps. In section 3, we present several of the sky coverage maps, and finally summarize our NFIRAOS sky coverage findings in section 4.

2. Method

In this section, we describe the steps we use to go from Monte Carlo simulations of NFIRAOS performance to all-sky performance maps of NFIRAOS. Median sky coverage will vary over the sky depending on the zenith angle (airmass) of the target at a given time (which can be characterized by the hour angle, the time before or after an objects transits the meridian) and the distribution of stars as a function of magnitude at that point in the sky. Running full Monte Carlo simulations for each zenith angle and stellar density over a range of asterisms is a hugely expensive computational problem.

We solve this problem by taking advantage of the split tomography approach, described in section 2.1, to decouple the high order errors from the LGS WFSs and the low order (dominated by, but not exclusively tip, tilt and focus) WFEs from the NGS OIWFSs. Once this problem has been decoupled, we can explore how the distribution of NGS WFEs varies as a function of stellar density, zenith angle, and input atmospheric profile (section 2.2). Finally, these results can be combined with the LGS WFEs to create sky coverage maps (section 3).

2.1. Split Tomography

We have used the Multi-threaded AO Simulator (MAOS) [4] to perform high fidelity Monte Carlo sky coverage simulations of NFIRAOS [5]. We simulate the Mauna Kea atmosphere (7 layer profile based on TMT site testing data [6]) using high spatial sampling and physical optics WFSs. We have set the split tomography algorithm [5] as the baseline for both simulations and the real time controller. For this control scheme, the LGS (high order) and NGS (low order) loops are driven independently. As shown in Figure 1, the LGS tomography step applies a minimum variance estimator to the tip-tilt removed, pseudo open loop LGS gradients. For these sky coverage simulations, we use a post processing step to calculate the

NGS error for each time step. The NGS WFE are low order WFEs that are unobservable to the LGS WFS on account of the LGS position uncertainty. During this step, we draw a large number (order 500) of random asterisms using the stellar densities for different parts of the sky. From these asterisms, the code determines the optimal configuration (and sampling frequency) of NGS for the OIWFS (if there are more than 3 available NGS) which minimizes the residual NGS WFE. This step can then be repeated for different input stellar densities. In this way, we save a great deal of computation time, as we do not have to perform the LGS tomography step for every asterism.

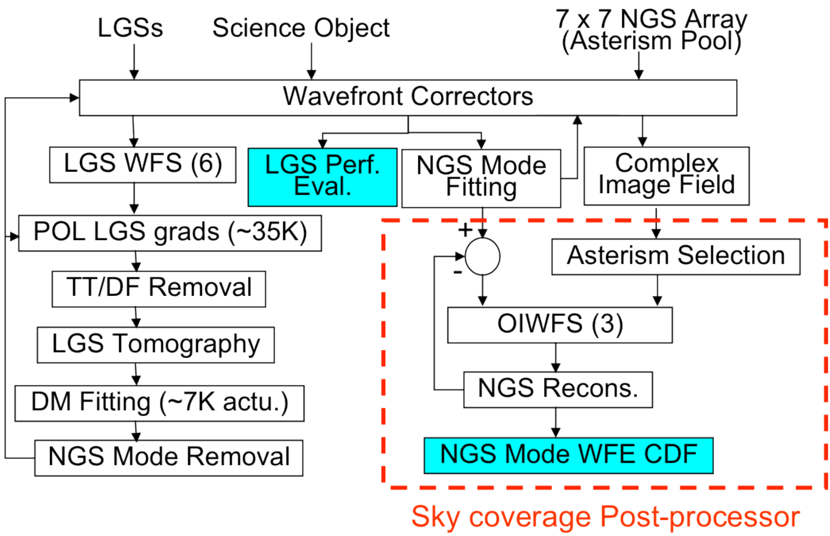

Fig. 1. Block diagram showing the process used for sky coverage simulations. The sky coverage post-processor can be run independently many times for many different NGS asterisms for each step of the LGS simulation.

2.2. Stellar Density and Zenith Angle Maps

With a process in place that allows us to study the performance for a large number of asterisms at different zenith angles and stellar densities, we can map NFIRAOS performance in terms of these two variables onto the sky. To do this, we initially need to create stellar density and zenith angle maps (as a function of hour angle). We decided to create the maps in galactic coordinates, since the sky coverage at high galactic latitudes is such a strong scientific driver for NFIRAOS.

The density of stars brighter than a certain magnitude at a given galactic latitude only gives part of the information needed for the simulations. The full distribution function of stars as a function of magnitude is needed in order to create realistic random asterisms. Since

NFIRAOS OIWFSs target sharpened NIR tip-tilt stars observed through a 30 m telescope, stars as faint as J<22 can be used. Unfortunately, no all-sky NIR stellar catalog exists to that depth at this time, so we rely on the statistical Besancon model of our galaxy [7]. By using this model, we can look at the stellar distribution functions at any point in the sky[b]. We find that at high galactic latitudes, the normalized distribution function does not vary significantly (Figure 2).

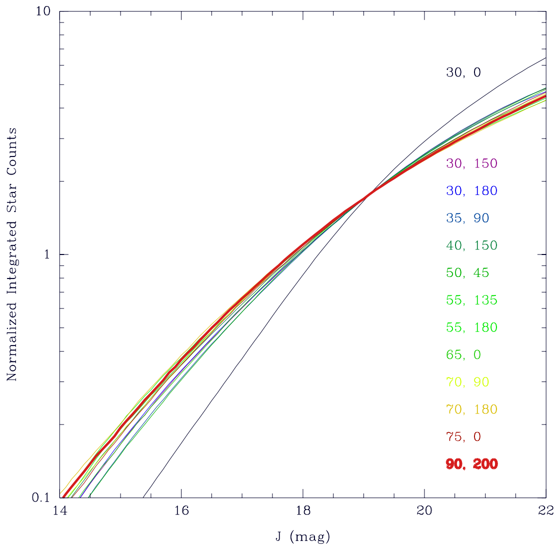

Fig. 2. Normalized integrated star counts for a number of high elevation positions in the Galactic plane (colored lines). When one probes closer to the plane, the shape of the distribution changes markedly as one begins probing the disk and bulge (black line).

By adopting a single normalized distribution function with a single offset (the number of stars with J<19), we can accurately model sky coverage out of the plane of the Milky Way. Once we start to probe closer to the plane of the Milky Way, the distribution function changes shape. Therefore, we use a single distribution function (taken for the North Galactic Pole where we are interested in the highest fidelity sky coverage estimates) and cap our model of the galaxy at 7500 stars/square degree with J<19 (Figure 3 left panel). By limiting our sky coverage simulations in this way, we are underestimating NFIRAOS sky coverage at low galactic latitudes, but as we shall show, NFIRAOS should deliver very high sky coverage in the plane of the Milky Way, even with this underestimate. Using the sky coverage post-processing steps described above, we have simulated 7 stellar densities: 2300, 2800, 3700, 4500, 5500, 6500, and 7500 stars/square degree with J<19 magnitudes.

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[b] Regions of high extinction are not included in the Besancon model, but those regions exist primarily in the disk of the galaxy where we are not attempting to accurately model.

Finally, we also have to compute maps of zenith angle in galactic coordinates for a given hour angle (Figure 3 right panel). We have created maps for several hour angles. In this paper, we focus on results for an hour angle of zero, as this shows the best sky coverage of NFIRAOS, but we also have created zenith (and WFE) maps for hour angles of 2 and 3 hours (to show the expected performance of NFIRAOS at the beginning of a 4 or 6 hour observation). We simulated NFIRAOS performance for 8 zenith angles: 0, 30, 45, 55, 57.5, 60, 62.5 and 65.

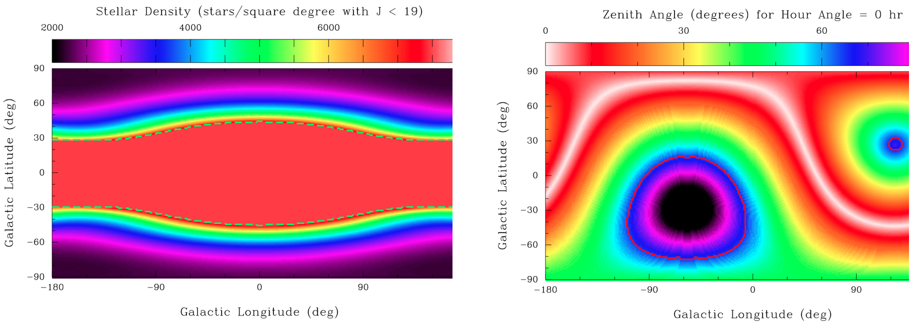


Fig. 3. Left Panel: Stellar density map in galactic coordinates. The green contour represents 7500 stars/square degree with J<19 and is the limit to which we fit galactic structure. Right panel: Zenith angle map for MK 13N and 0 hr of H.A. The red contours represent a zenith angle of 65 degrees.

The sky coverage post-processing tool was used to simulate 7 stellar densities, 8 zenith angles, quartiles in atmospheric seeing, 500 random asterisms over 5000 time steps (800 Hz) for 4 random atmospheric turbulence seeds for a total of almost 1.7 billion simulation steps. We created data cubes which contained WFEs for each of the 500 asterisms for the 7 stellar densities and 8 zenith angles. We then, for example, generate interpolation functions that yield NFIRAOS NGS WFE for the median atmosphere as a function of zenith angle and stellar density. We then map this interpolation function onto the zenith and density all sky maps above to produce NFIRAOS sky coverage maps of NGS WFEs. In a similar fashion, we produce high order LGS + implementation WFE maps which only depend on zenith. The low order NGS WFE maps can then be combined with the higher order LGS+implementation WFE maps in quadrature yielding NFIRAOS performance estimates over the entire sky.

3. Sky Coverage Maps

Figures 4 and 5 provide an overview of the most important NFIRAOS all-sky performance maps. In Figure 4 we see the median WFE across the entire sky in galactic coordinates for an hour angle of 0 hr (i.e. when objects will be closest to zenith) for the median, random guide star asterism. Assumptions about stellar number counts only hold above and below the green lines (WFEs are somewhat over-estimated near the galaxy plane). The red lines mark a zenith angle of 65 degrees, below which NFIRAOS is not required to observe. NFIRAOS can observe most of the accessible sky and deliver total WFEs less than 190 nm for at least 50% of guide star asterisms. Figure 5 shows the probability of achieving 191 nm of WFE for random guide star asterisms and the median atmospheric profile, again for an hour angle of 0 hr. In the galaxy plane, there are always enough guide stars to deliver 191 nm of WFE. 70% of random asterisms near the North Galactic Pole meet this requirement.

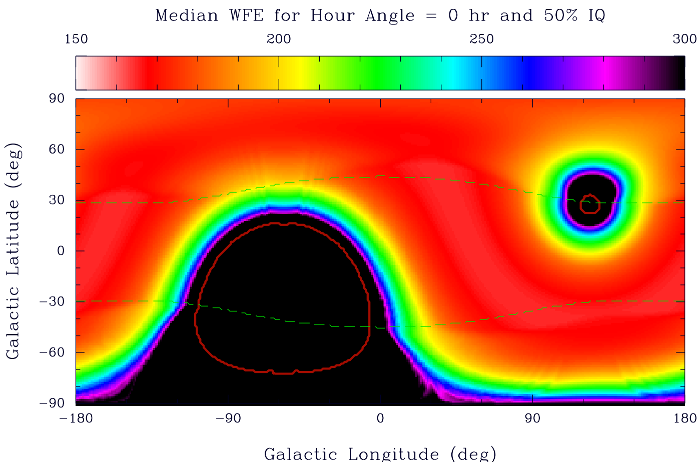


Fig. 4. Median NFIRAOS WFE all-sky map.

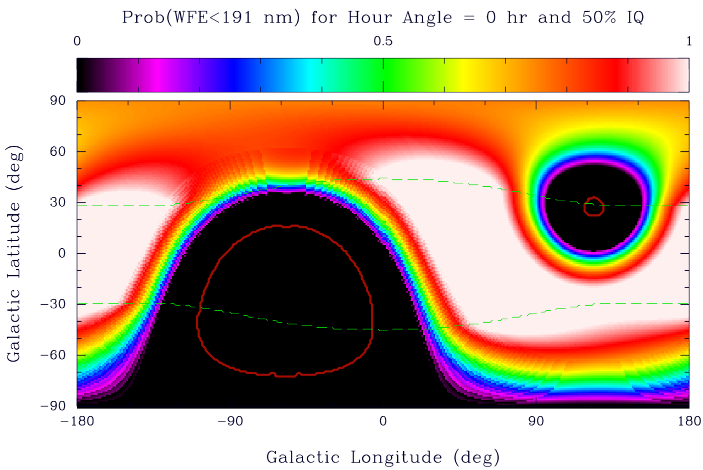
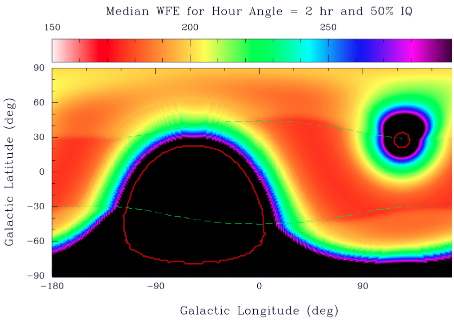


Fig. 5. Probability map of NFIRAOS achieving 191 nm of WFE.

Sky coverage maps such as those shown above can be used to explore NFIRAOS performance under a wide variety of conditions. We have produced maps for different hour angles (e.g. one would optimally start a 4 hr observation at an H.A=-2 hr), 25% and 75% sky coverage (in terms of the percentage of random asterisms that yield a given WFE), and quartiles in atmospheric image quality. Sky coverage maps therefore prove useful in assessing the real-life expected performance of NFIRAOS under a multitude of conditions. Figure 6 shows examples of NFIRAOS performance for an H.A.=2 hr under median conditions and for an H.A.=0 hr, but under the 25% best image quality we expect at MK 13 N.



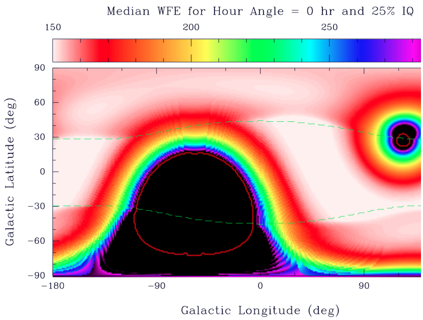


Fig. 6. Left Panel: NFIRAOS performance for HA=2 hr (which allows 4 hours of observing with this performance – and better). The WFE < 210 nm RMS over most of the observable sky. Right Panel: NFIRAOS performance for an atmosphere that delivers the 25% best image quality. The WFE<160 nm RMS over most of the sky in these favorable conditions.

For the TMT instrument teams, we have also produced maps of delivered Strehl ratios (Figure 7) and are working on producing maps of delivered ensquared energy within, for example, an IRIS IFU spaxel (the ensquared energy within a spaxel larger than the TMT diffraction limit should be significantly larger than the corresponding Strehl ratio because low spatial order WFEs will not scatter light out of the spaxel; these WFEs will just broaden the core).

4. Summary

From our analysis, we conclude: 1) the maps are consistent with the NFIRAOS error budget, 2) NFIRAOS delivers reasonable WFEs even at moderate zenith angles (or Hour Angles) for at least 50% of random asterisms, 3) NFIRAOS performance should be excellent over a large fraction of the sky when there is a favorable turbulence profile, 4) as already known, performance deteriorates quickly with zenith angle, and 5) the probability of achieving useable performance also drops rapidly with guide star density, especially at moderate zenith angles.

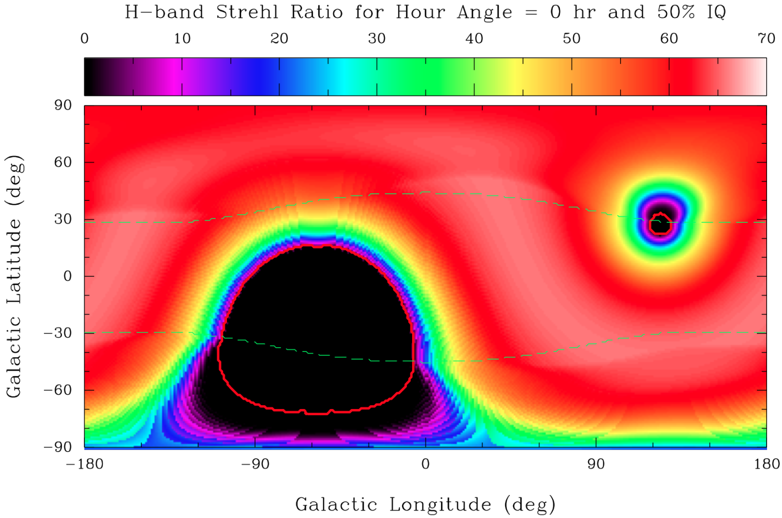


Fig. 7. H-band Strehl ratio map for an HA=0 hr, median sky coverage, and 50% image quality. NFIRAOS should deliver Strehl ratios greater than 60% over most of the observable sky for at least half of the fields.

5. References

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