Full Physical Optics Sky Coverage Analysis for MCAO Systems on ELT’s

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Outline

- The TMT NFIRAOS system
- Approach to sky-coverage analysis
  - Monte Carlo simulation of multiple NGS guide fields
  - Time domain AO simulations with physical optics modeling of LGS and NGS wavefront sensors
  - “Split tomography” control enables an efficient approach
- Optimization of the wavefront sensing and control algorithm parameters for the low-order NGS WFS
- Sky coverage results summary
NFIRAOS is a “Narrow” Field Infrared Multi-Conjugate LGS AO system
- 2 DM (order 63x63 and 76x76, 0.0 and 11.2 km)
- 6 LGS (order 60x60, 35” radius asterism)
- 2’ diameter patrol field for the low-order NGS WFS
- 3 output ports for instruments with fields from 2” to 2’
  - IRIS 10”x10” science field for this analysis

J+H Band Infrared low order NGS wavefront sensing
- Controls 2 tip/tilt, 3 plate scale modes, and LGS focus uncertainty
- 1 tip/tilt/focus (TTF) + 2 tip/tilt (TT) NGS WFS
- Adjustable 10-800 Hz NGS frame rate
- Read out noise: 0-10 electrons for this analysis
- Quantum efficiency: 0.8 (J), 0.8 (H)
- Optical throughput: 0.4
NFIRAOS Split Tomography
Control Architecture

- Separate control loops employed for LGS- and NGS-controlled modes
- NGS-controlled modes are tip/tilt and “plate scale” modes
  - Induce tip/tilt and quadratic errors in NGS WFS measurements and science wavefronts
  - Invisible to LGS WFS
  - The LGS loop performance is not effected by the NGS loop
The three plate scale modes
- Majority of tilt anisoplanatism modes
- Produces field dependent tip/tilt
- Also produces high order (quadratic), field invariant distortion of the wavefront

Field distortion of the three Plate Scale modes
How Split Tomography Enables Efficient Sky Coverage Analysis

First run high order LGS AO simulation
- correct NGS modes perfectly using best-fit coefficients
- store time history of the NGS modes and the complex PSF of NGS on a 7x7 grid

Post processing
- Pick a random asterism and generate the NGS PSF by interpolation on the 7x7 grid
- For each time step
  - Add residual NGS mode errors back to the NGS PSF
  - Take NGS WFS measurements and apply NGS reconstructor
  - Apply correction to the NGS modes in close loop.
  - Estimate the wavefront error
- Optimize the NGS sampling frequency
- Collect statistics
NGS PSF Modeling

- Need to restore residual tip/tilt and plate scale wavefront errors into the NGS PSF.
- A simple FFT shift to model tip/tilt is not accurate.
- We instead store the complex PSF core, Inverse FFT to obtain the coarsely sampled complex pupil function, apply the phase distortion caused by tip/tilt and plate scale modes, and finally FFT to form the PSF.

<table>
<thead>
<tr>
<th>Compare:</th>
<th>True PSF</th>
<th>FFT Shift 21% Error</th>
<th>Complex PSF 4% Error</th>
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<tbody>
<tr>
<td>A large amount of mode 3</td>
<td>True PSF</td>
<td>FFT Shift 21% Error</td>
<td>Complex PSF 4% Error</td>
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- This post processing technique is validated against the integrated LGS+NGS simulations
Median Sky Coverage Results

- Nominal NFIRAOS system parameters
- Median atmosphere conditions: $r_0=0.15\text{m}$, $L_0=30\text{m}$
- 75% wind shake, 20 mas
- Galactic Pole (Besancon)
- T/T: 47.4 nm
- Total NGS: 63.4 nm
- Various optimizations on NGS wavefront sensing and control algorithm have been made to achieve this.
Improvements to the NGS Wavefront Sensing

- Classical matched filter pixel processing without linearity constraints
  - reduces sensitivity to measurement noise
  - 50 nm (in quadrature) improvement over constrained matched filter
  - 70 nm improvement over thresholded center of gravity ($3\sigma$ threshold)

- Adaptively “demote” the TTF WFS to a TT WFS by averaging the measurements for global tip/tilt estimation
  - Found to generally improve performance with bright TTF NGS
  - 58 nm reduction in TT modes at median sky coverage

- Large pixel width ($\lambda_H/d$ instead of $\lambda_J/d$) to fully contain the PSF core in H band
  - 29 nm reduction in total NGS modes

- Optimize higher-order (LGS) correction for a wider field
  - Improves NGS “sharpening”, with negligible effect on on-axis performance
  - More on next page
LGS Control Algorithm Impacts NGS “Sharpening” and Sky Coverage

Broadening the DM “fitting FoV” from 10” to 30”

- Off axis Strehl is greatly improved
- Reduction to on-axis Strehl is small
- 41 nm reduction in tip/tilt mode, and 60 nm reduction in overall NGS modes at median sky coverage
Improvements to the NGS Loop Control Algorithm

- **Type II control of the NGS plate scale modes**
  - Double integrator with a lead filter
  - Helps to reduce the servo lag error
  - 37 nm reduction (in quadrature) in plate scale modes in median sky coverage

- **Improved Type II control of the tip/tilt modes, optimized for measured 90 Hz response of the CILAS TTS**
  - Double integrator with a lead filter
  - 17 nm reduction in tip/tilt modes
189 nm total RMS wavefront error in media sky coverage
- 178 nm in LGS mode
- 63 nm in NGS

Overall on-axis budget of 187 nm RMS is met at 45% sky coverage

Shortfall (in quadrature) of ~28 nm RMS at median sky coverage

System optimization still underway
- Detector performance
- “Fitting field” for LGS modes
- Optimal choice of NGS modes and reconstructor
Performance Improvement vs. Changes in Operating Conditions

- Wavefront error reductions (in quadrature) compared with nominal case
- Improvement of 60-70 nm RMS at median sky coverage
Performance Variations with Detector Size and Read Noise

- Incremental wavefront error for detectors with:
  - RoN:5e  51nm
  - RoN:10e  73nm
- $\lambda_H/d$ pixel width better than $\lambda_H/2d$
  - Except RoN=0 detectors (equal performance)
Sky Coverage Results for Enclosed Energy on 4, 9, and 25 mas Detectors
Summary of Key Results

- We have implemented a high fidelity, physical optics sky coverage simulation in the time domain.
- Nominal performance estimates for NFIRAOS+IRIS are encouraging:
  - 47.4 nm tip/tilt error and 63.4 nm total wavefront error in the NGS-controlled modes with 50% sky coverage at the galactic pole.
  - Overall NFIRAOS wavefront budget is met at 45% sky coverage.
  - Budget exceeded (in quadrature) by 28 nm at 50% sky coverage.
- Performance analysis/optimization is continuing:
  - Detector parameters.
  - Choice of DM “fitting field”.
  - Optimal choice of NGS modes and reconstruction algorithm.
- Performance improvements with 25% seeing or 30 degrees galactic latitude are significant.
- Sky coverage analysis in terms of PSF parameters is in process.
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