Using Site testing data for Adaptive Optics simulations

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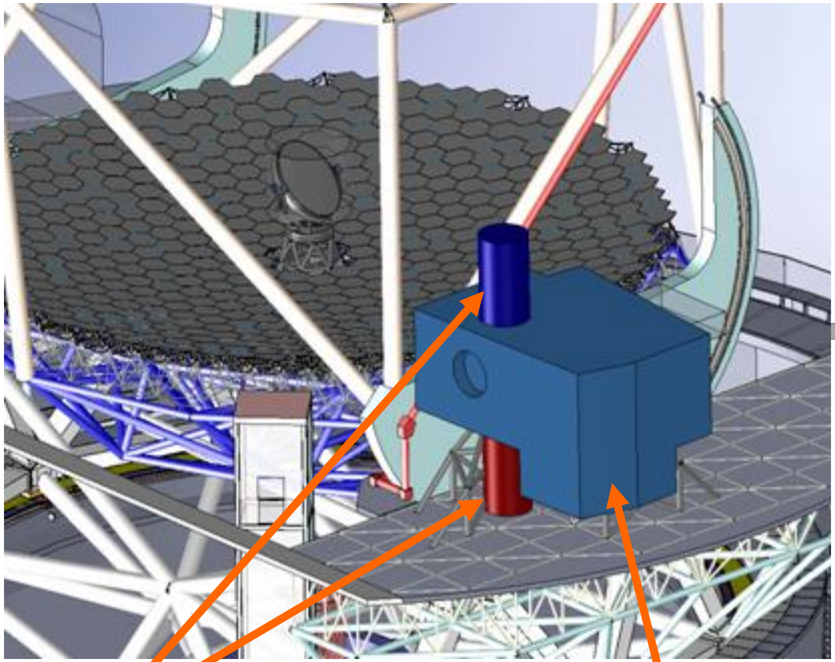
Outline

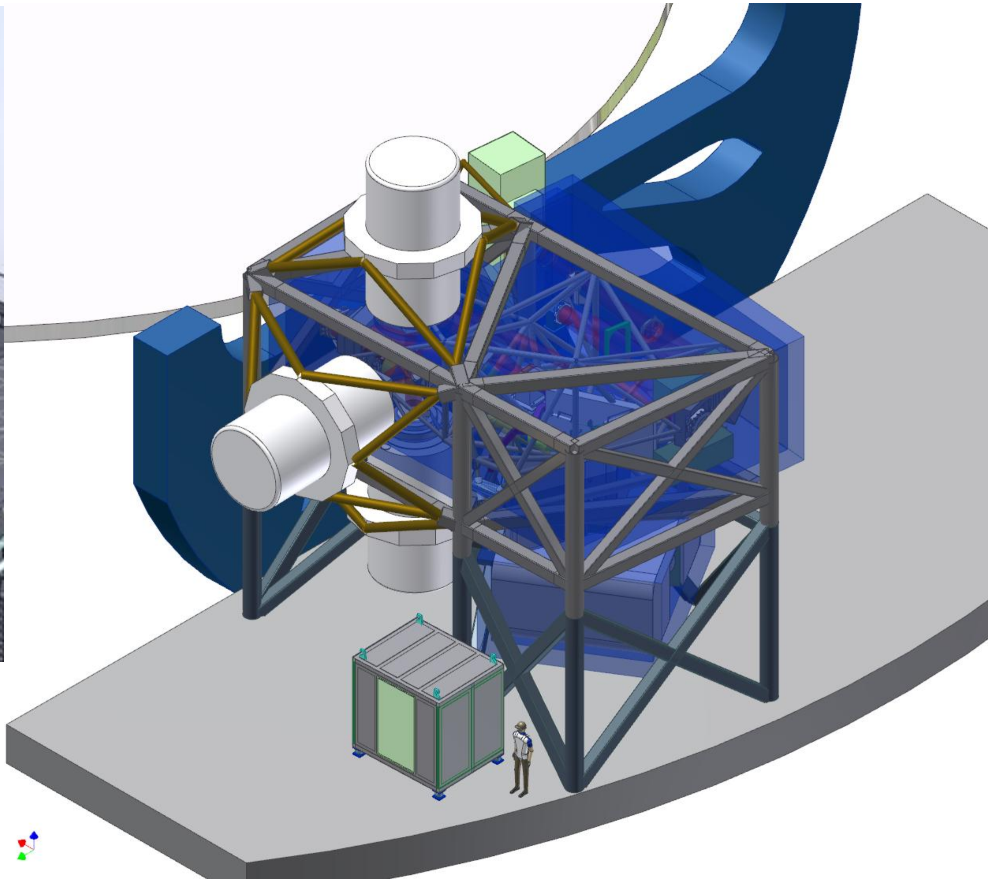
- TMT / NFIRAOS
- Site Testing Parameters and their value for Adaptive Optics Simulations
- Sky coverage
  - Performance models vs season, site
- DM Stroke requirement
- Diameter of Laser launch telescope
- Sodium layer structure
  - Matched filters
  - Meteor tracking
- AR model of seeing
  - Centroid gain estimate in real time

NFIRAOS
on TMT Nasmyth platform



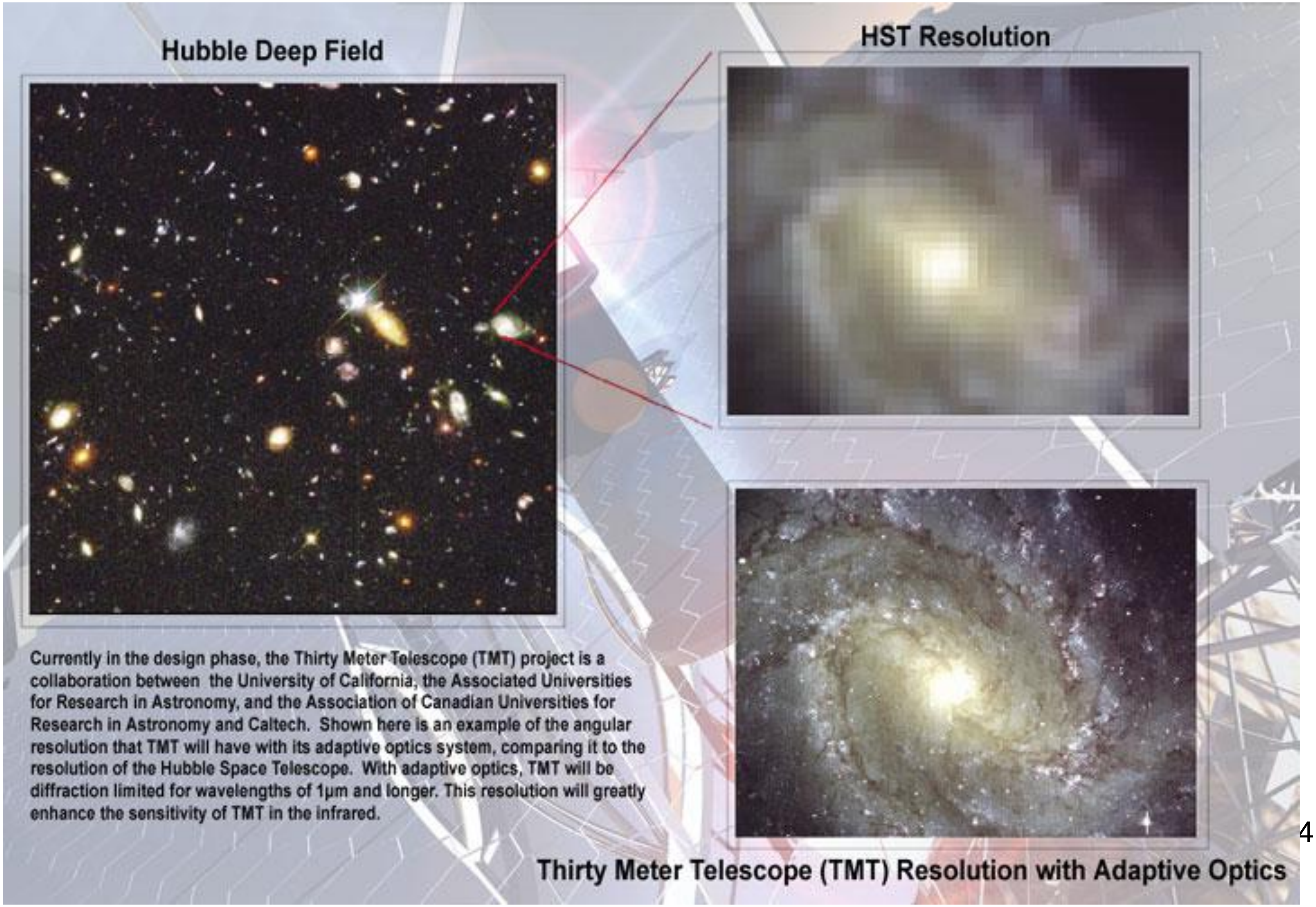
Instruments

Space envelope
Allocation for
NFIRAOS



Current Design

Working at the Diffraction Limit
Thirty Meter Telescope



Currently in the design phase, the Thirty Meter Telescope (TMT) project is a collaboration between the University of California, the Associated Universities for Research in Astronomy, and the Association of Canadian Universities for Research in Astronomy and Caltech. Shown here is an example of the angular resolution that TMT will have with its adaptive optics system, comparing it to the resolution of the Hubble Space Telescope. With adaptive optics, TMT will be diffraction limited for wavelengths of 1μm and longer. This resolution will greatly enhance the sensitivity of TMT in the infrared.

Thirty Meter Telescope (TMT) Resolution with Adaptive Optics

NFIRAOS Top-Level Requirements

- **Throughput** 85%, 0.8 to 2.5 μm
- **Background** Thermal emission < 15 % of sky and telescope
- **Wavefront Error** 187 nm RMS on-axis, and 191 nm on a 10” FoV
- **Sky coverage** 50 per cent at the Galactic pole
- **Differential photometry** 2% for a 2 minute exposure on a 30” FoV at $\lambda = 1\ \mu$m
- **Differential Astrometry** 50 μas for a 100 s exposure on a 30” FoV in the H band
- **Available** from **standby** <10 minutes
- **Acquire** a new field < 5 minutes
- **Downtime** unscheduled < 1 per cent

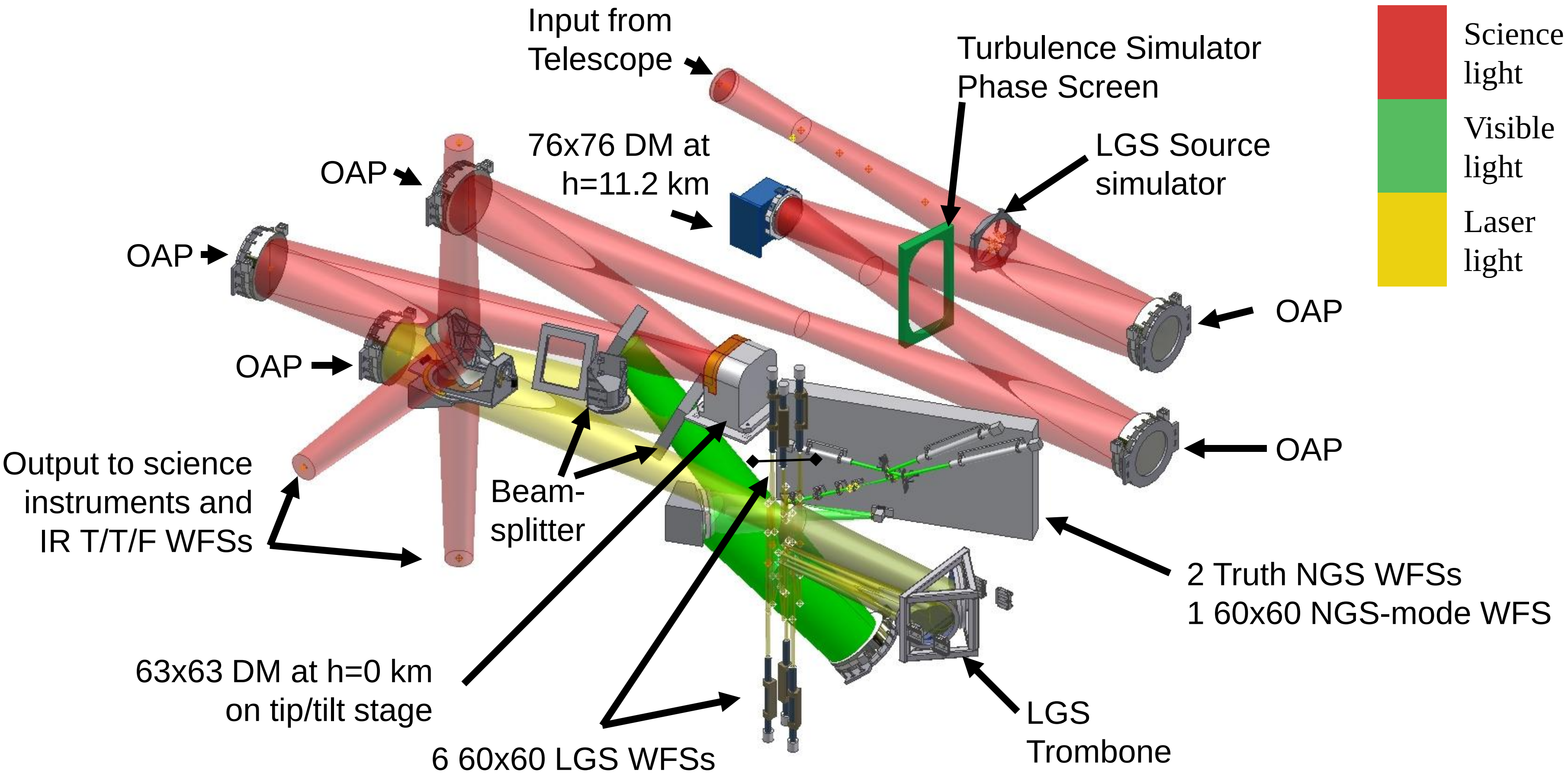
NFIRAOS Architecture

- **Atmospheric tomography** with **six laser** guide stars
- Near **infra-red tip/tilt & focus** sensing on **3** “sharpened” natural guide star images, within client instruments
- **Multi-conjugate** wavefront correction (also helps sky coverage)
- **Minimum surface count** (7 reflections + B/S + window)
- System **cooled** to -30 Celsius

Fundamental Design Parameters NFIRAOS

- 2 arcminute field
- 6 Laser WFSs order 60x60 in a 70-arcsecond diameter asterism
  - Polar Coordinate CCDs
  - 204792 pixels → 5792 gradients per WFS
- Control also uses client instruments' Wavefront sensors: 1 Tip/Tilt/Focus and 2 Tip/Tilt
  - sensing near-Infrared natural guide stars at 10 - 800 Hz.
- Two Piezo Stack DMs of 63x63 and 76x76 actuators
  - DM0, optically conjugate to ground, on Tip/Tilt stage
  - DM11, conjugate to 11.2 km.
- Real Time Controller solves 35K LGS WFS slopes x 7000 DM actuator tomography problem at 800 Hz.

NFIRAOS Opto-mechanical Layout



Input from Telescope

Turbulence Simulator Phase Screen

76x76 DM at h=11.2 km

LGS Source simulator

OAP

OAP

OAP

OAP

OAP

Output to science instruments and IR T/T/F WFSs

Beam-splitter

2 Truth NGS WFSs
1 60x60 NGS-mode WFS

63x63 DM at h=0 km on tip/tilt stage

6 60x60 LGS WFSs

LGS Trombone

🟥 Science light

🟩 Visible light

🟨 Laser light

Parameters of interest for Adaptive Optics

- r_0 Seeing and evolution of seeing vs. time
- $\Theta_{0 \ldots}$ Θn Isoplanatic Angle, generalized for N DMs
- L_0 Outer scale of turbulence
- τ_0 time constant for turbulence evolution
- Cn^2 vs altitude
  - and time evolution of Layers' strength vs time
- Wind speed vs altitude
- Ground Level Wind-speed – windshake vs dome seeing
- Sodium layer structure, abundance and time variation
- Ground level temperature and variation with time
- Sky transparency vs time.

What is the interest of Adaptive Optics in r_0 Seeing ?

- r_0 Seeing Affects
  - number of actuators needed on DMs
    - And number of subapertures on Wavefront sensors
  - Stroke on actuators
  - Laser guide star power required
  - Sky coverage (probability of achieving astronomy)
  - Computing power in real time computer

- Time evolution of r_0 affects update rate and accuracy of background tasks to optimize Adaptive optics control loops.

Value for Adaptive Optics in L_0 Outer scale of turbulence?

- L_0 Outer scale of turbulence
- Affects DM stroke required
  - Smaller L_0 means less stroke needed for the same r_0.
- Affects Tip/Tilt Focus stroke and bandwidth
  - Smaller L_0 means less energy in low modes and low frequencies
- Affects Phase screens for turbulence simulation
  - for both optical and numerical simulations

- Time evolution of L_0 affects background tasks, which optimize Adaptive optics control loops.

$\Theta_{0\ ,\ ,}\Theta n$ Isoplanatic Angle generalized for N DMs

- $\Theta_{0\ ,\ ,}\Theta n$ Isoplanatic Angle, generalized for N DMs
- Affects corrected field of view
- Thus affects sky coverage
  - Because tip/tilt/focus stars should be found in corrected field.
- Affects optimal number of DMs
  - And their ideal altitude of conjugation
- Affects number of Laser Guide Stars
  - And their spacing on the sky
- Affects number and location of optical phase screens in turbulence simulator

τ_0 time constant for turbulence evolution

- τ_0 affects bandwidth for AO control system
  - Readout rate of WFS
  - Laser power, read noise of WFS
  - Computer speed of real time controller

Parameters of interest
C_n^2 vs altitude

- C_n^2 vs altitude
  - Determines Number of layers in tomographic reconstruction and thus computing power
  - Defines DM quantity and Optimal altitude of conjugation
  - Good initial data allows quick settling of tomography algorithm to final value to begin science exposure
  - Determine potential effectiveness of a Ground Layer AO system.

Parameters of interest Wind speed vs altitude

- Wind speed vs altitude
  - Frozen flow
  - Predictive filter methods are desirable,
  - But how effective are they? Simulations can tell us, providing that we have good data.

Parameters of interest Wind speed vs altitude

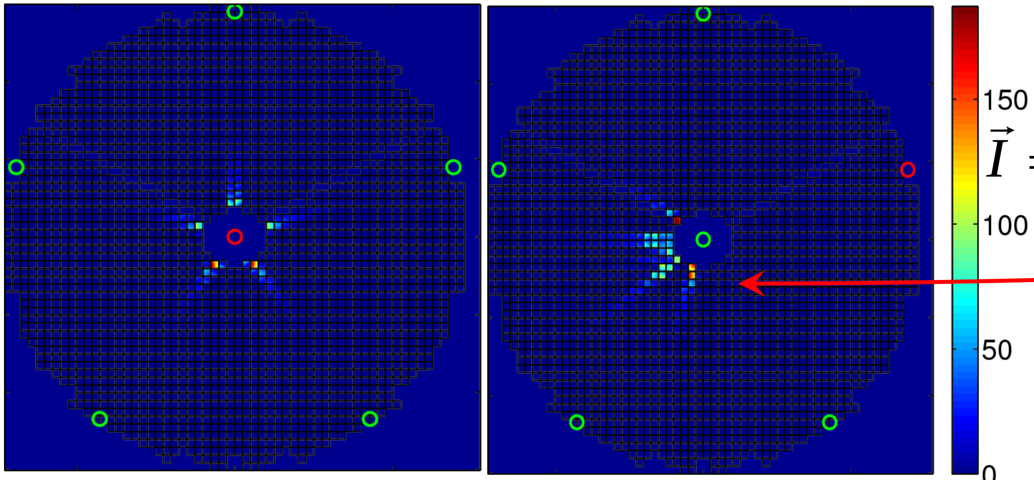
- Ground Level Wind speed
  - Windspeed data feeds Dome Computational Fluid Dynamic wind force models, which are applied to TMT structural finite element models and controls model of telescope and mirror segments.
  - Resulting windshake is disturbance input to NFIRAOS simulations of performance and sky coverage
- Dome computational fluid dynamics and heat transfer models create dome seeing voxel (volume elements) maps within dome.
- Ray tracing through dome voxel dome creates phase screens
  - Input to Adaptive Optics simulations.

Parameters of interest
Ground level temperature vs time.

- Ground level temperature variation with time
  - Temperature variation of telescope and dome cause dome seeing
  - Near-IR background flux from warm telescope optics increases integration time for background limited objects.
  - Point Source sensitivity calculations affected

Fraction of nights with Sub-visible cirrus causing Fratricide and Scattering

- Four scattering effects studied: Rayleigh, ozone, aerosol, cirrus
  - Rayleigh scattering induces fratricide between LGS WFSs <u>for Central Launch</u>



Incremental WFE (nm)

$$\vec{I} = \mathrm{P}(\vec{I}_{nf}) + \sigma_e \mathrm{N}(0,1) + \mathrm{P}(\vec{I}_{bkg}) - \overset{0.8}{\alpha_{cal}}\,\vec{I}_{bkg}$$

Computed by integrating the atmospheric backscattered light intensity profile (volume scattering coefficient) over altitude, subaperture area, and pixel FoV.

Zenith angle (deg)	0	30	45	60
% affected subaps	0.4	0.7	1.5	4.6
0% calib.	12	20	39	117
80% calib.	1	5	10	31

  - Real-time updates at ~0.1Hz are expected to provide required calibration accuracy to better than 80%

- Ozone, aerosol and cirrus contribute to momentary signal level variations <u>for both CL and SL</u>: ~23 nm RMS for 20% reduction

Telemetry from AO systems continues to “survey” site.

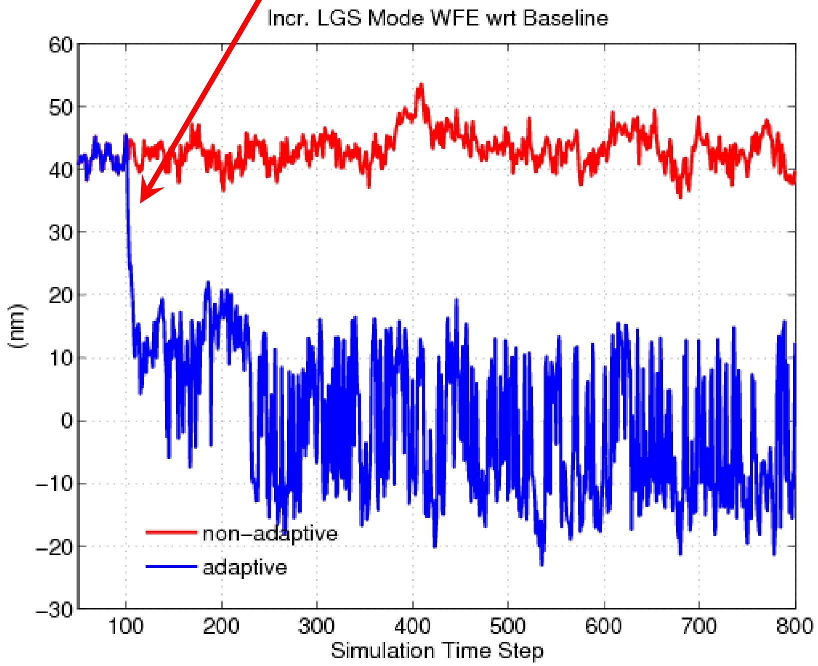
- Telemetry from Adaptive Optics Systems can continue to monitor sites.
- Classic AO System
  - Gemini Altair outputs r_0 and L_0 based on Telemetry
- –for Gemini Gpi AO system – Poyneer & Veran –
  - Simulations using Gemini Altair and NICI Telemetry says GPi can determine Number of atmospheric layers and wind speed for each
  - But not the altitude and strength of each layer
- While there is a good fraction of turbulence that appears to be frozen flow, there is also a significant portion that is not. All proposed AO predictive control schemes currently assume frozen flow...

Real-Time Cn2 Profile Estimation for Optimal Tomographic Wavefront Reconstruction

- SLODAR-like method correlates pseudo open-loop measurements from a pair of the 6 NFIRAOS LGS WFSs
- Eliminates sensitivity to LGS tip/tilt/focus by using second-order differences of gradients
- Computationally efficient and convergent in a few hundred frames at 800Hz
- Vertical resolution $\delta h = \Delta / (\theta_1 - \theta_2) \sim 1$ km
  - 6 layers estimated from 11 baselines
  - Solves linear system of the form

    $$Ax = b \quad x_k = r_{0k}^{-5/3}$$

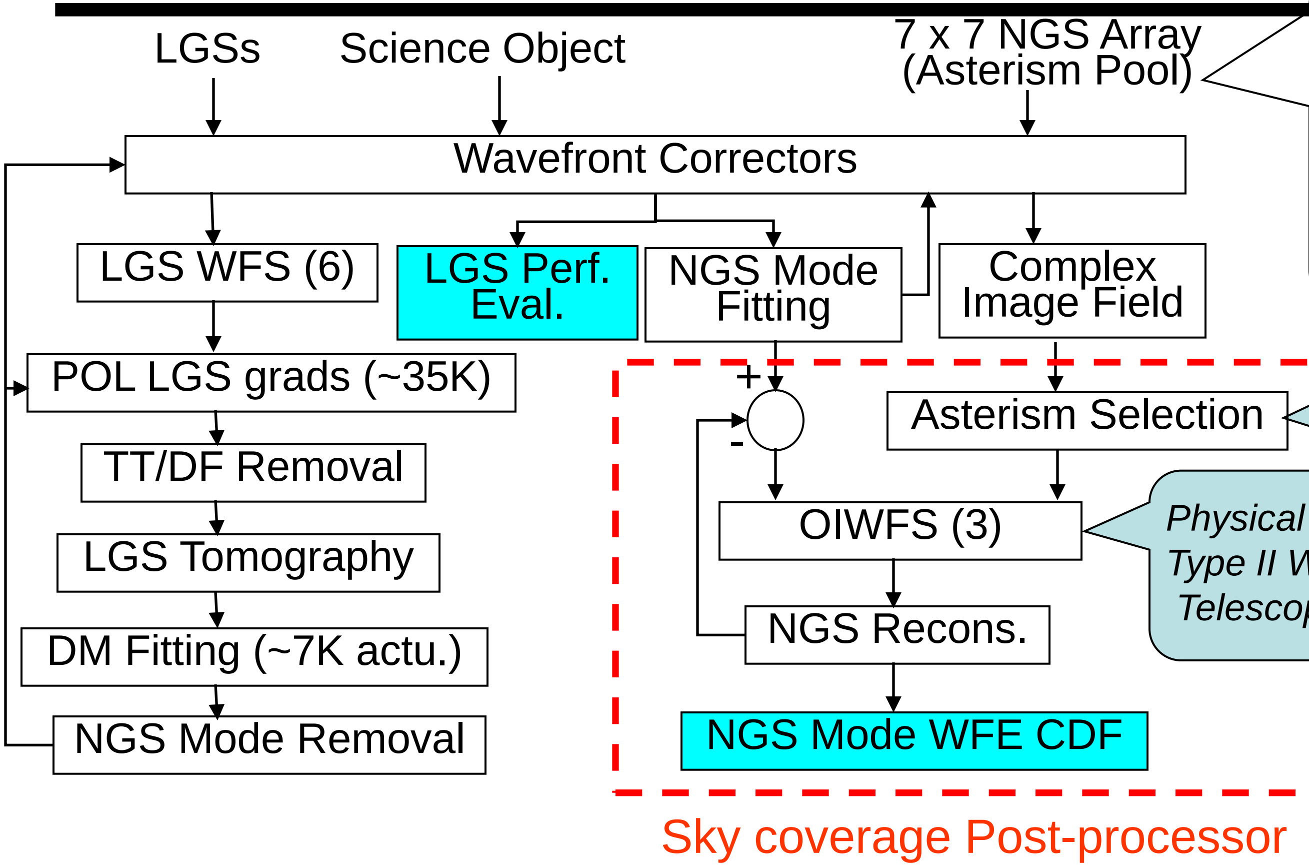
    A computed using Fourier technique



TMT Error Budgeting and Performance Analysis

- Comprehensive evaluation of TMT AO architecture
  - Wavefront disturbances due to atmosphere/telescope/NFIRAOS/instruments
  - NFIRAOS wavefront sensing and correcting hardware
  - LGSF and OIWFS components
  - NFIRAOS processing algorithms
- Performance evaluation as a function of seeing, zenith angle, field of view and galactic latitude
- Estimates developed through a combination of:
  - Integrated AO simulations
  - Side analyses
  - Budget allocations
  - Lab and LIDAR experiments

Simulation Tools for LGS Performance Analysis and Sky Coverage Evaluation



LGSs

Science Object

7 x 7 NGS Array (Asterism Pool)

Wavefront Correctors

LGS WFS (6)

LGS Perf. Eval.

NGS Mode Fitting

Complex Image Field

POL LGS grads (~35K)

TT/DF Removal

LGS Tomography

DM Fitting (~7K actu.)

NGS Mode Removal

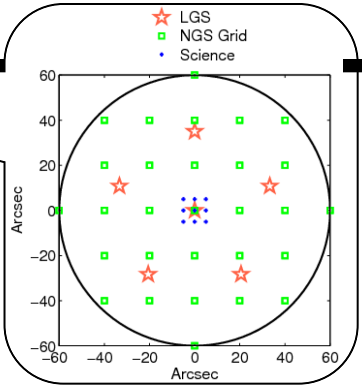
Asterism Selection

OIWFS (3)

NGS Recons.

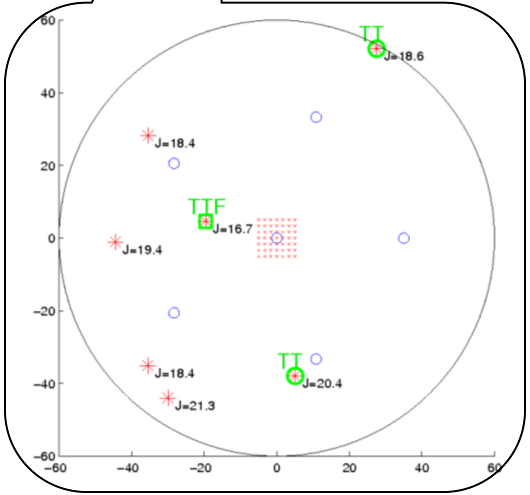
NGS Mode WFE CDF

Sky coverage Post-processor



500 guide star fields

Physical optics model
Type II Woofer/Tweeter control
Telescope windshake PSD



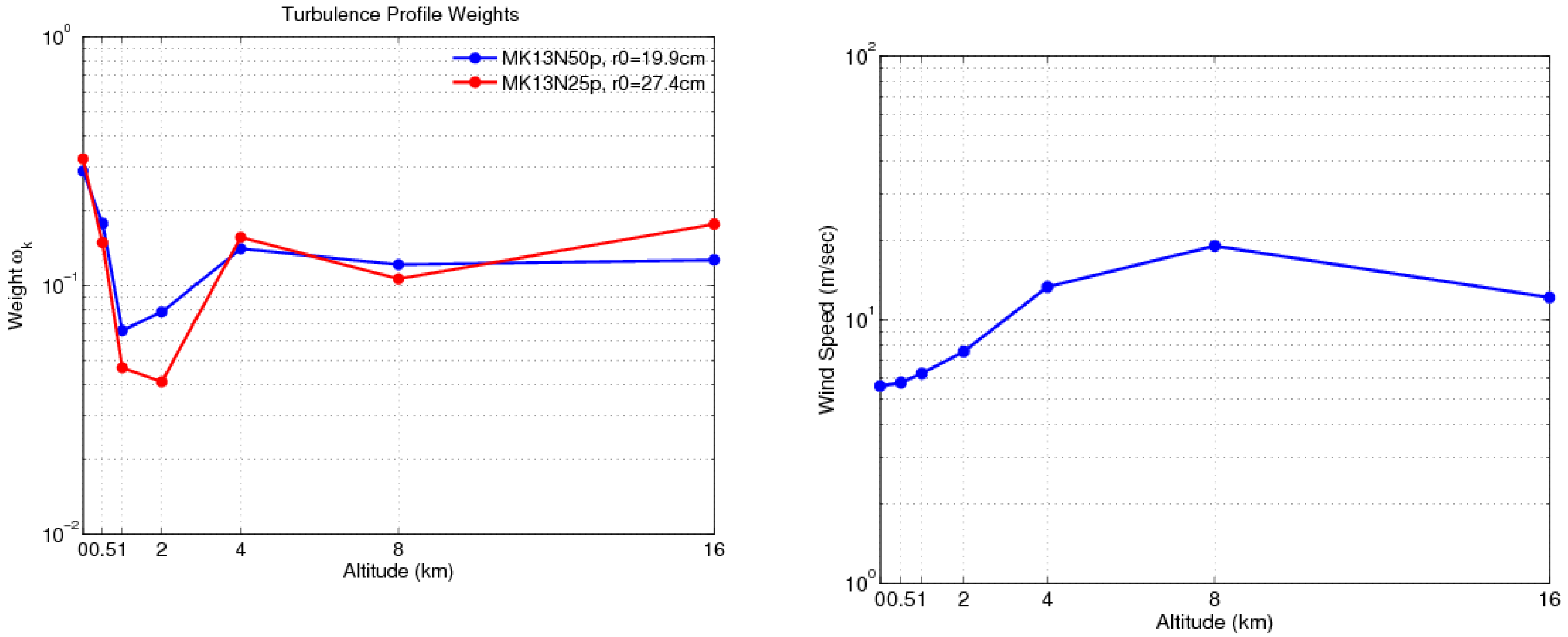
Key Results Over the Last Two Years

- Performance analysis for Mauna Kea confirms that performance requirements are met:
  - 187 nm on-axis at zenith with median seeing and 50% sky coverage at the Galactic Pole met with 83 nm RMS margin in quadrature
  - Based upon detailed time domain simulations of NFIRAOS, including WFSs, DMs, RTC, and telescope models
- Sky coverage has been evaluated and optimized in detail:
  - Physical optics modeling of OIWFSs
  - Monte Carlo simulations over 500 guide star fields
  - Evaluation as a function of zenith angle and seeing
  - OIWFS Pixel processing and temporal filtering algorithms studied in detail

Turbulence Parameters for 25% & 50% Mauna Kea conditions

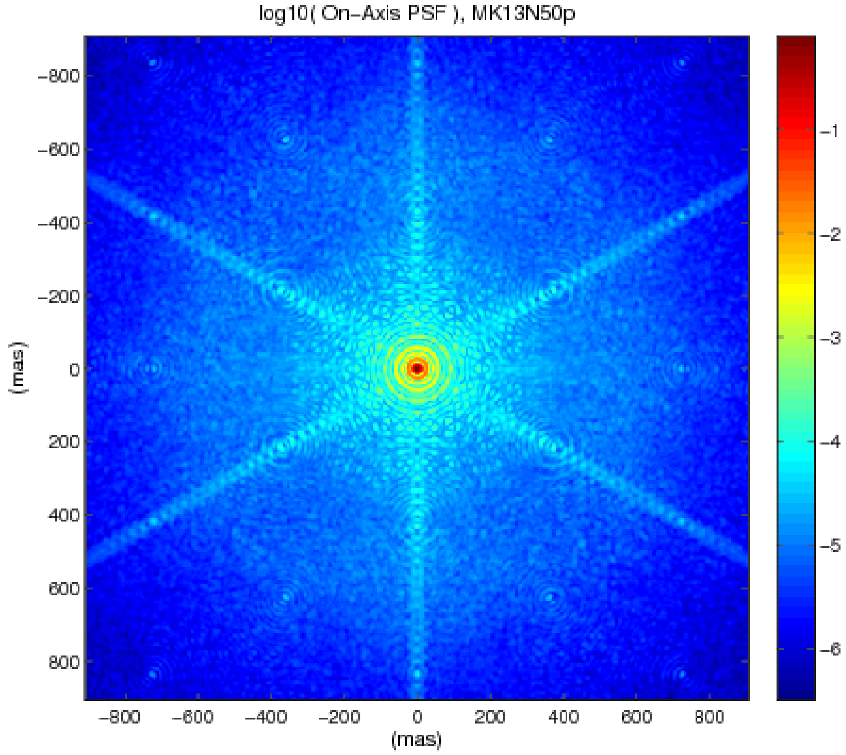
Altitude (km)	0	0.5	1	2	4	8	16
Wind Speed (m/s)	5.6	5.8	6.2	7.6	13	19	12
MK13N 25% profile, r0= 27.4 cm, θ_0 =2.7”, f_G=15.9Hz							
Weights (%)	32	15	4.7	4.1	16	11	18
MK13N 25% profile, r0= 19.9 cm, θ_0 =2.2”, f_G=21.7Hz							
Weights (%)	29	18	6.6	7.8	14	12	13

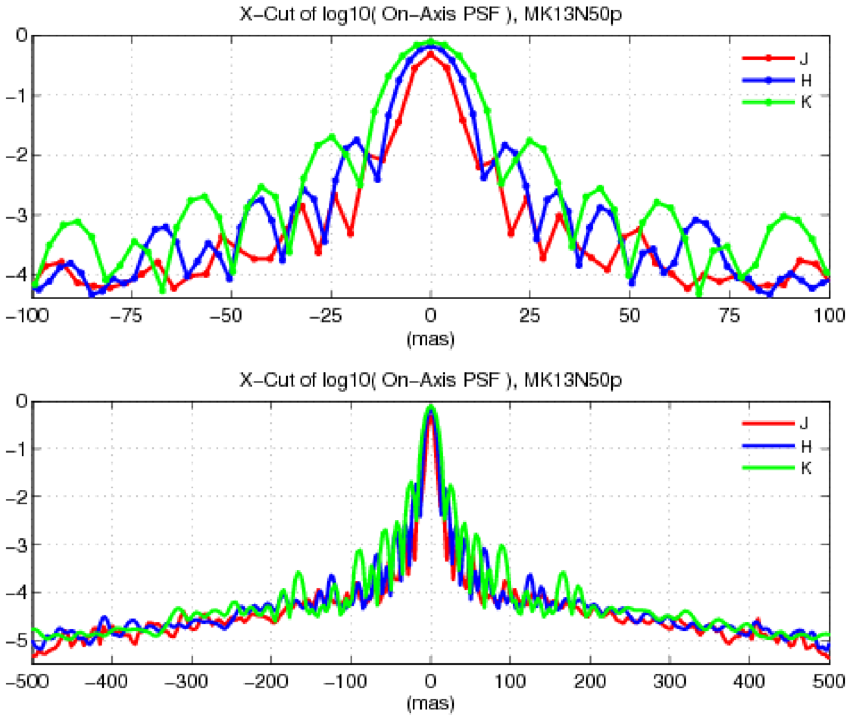
Winds aloft, and Cn^2 for Median and Good Seeing at Mauna Kea



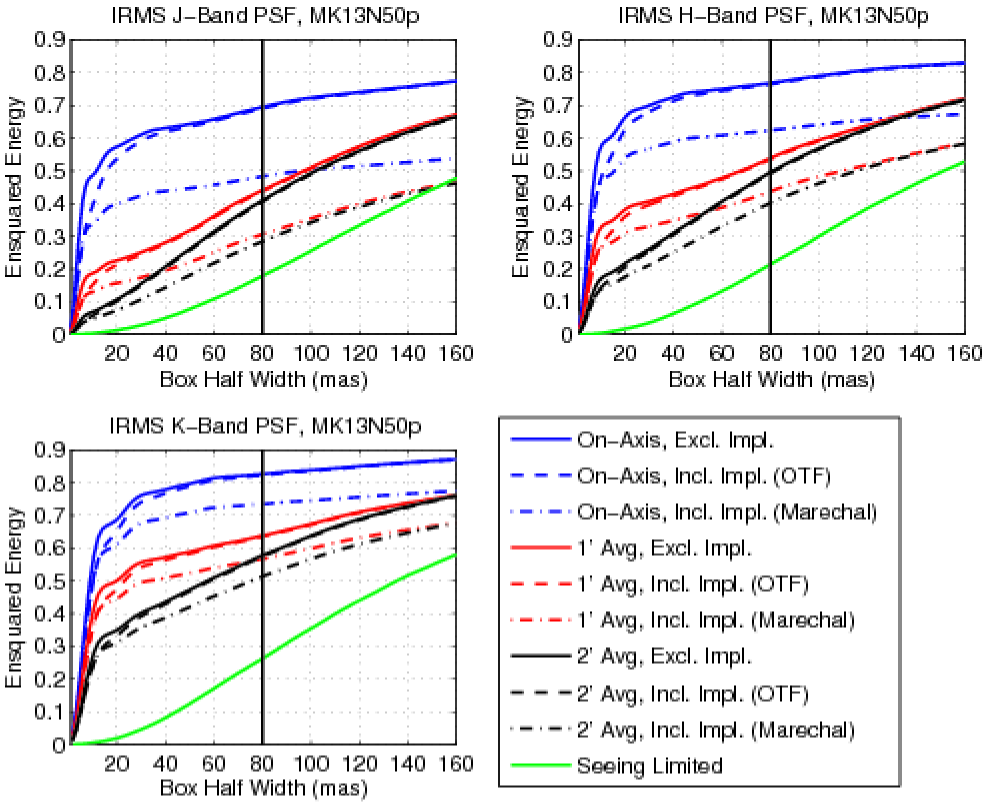
- Left: Turbulence profile relative weights (50% blue, 25% red). Right: Wind speed profile used in conjunction with the turbulence profiles shown on the left. from TMT.AOS.TEC.10.009.DRF01

NFIRAOS PSF for Mauna Kea





TMT NFIRAOS feeding multi-slit spectrograph (IRMS)

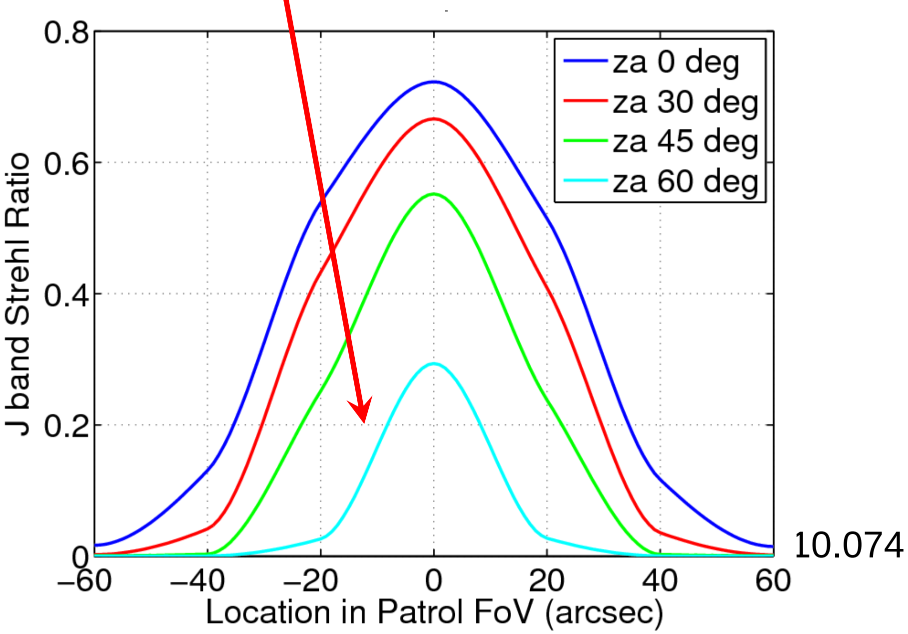


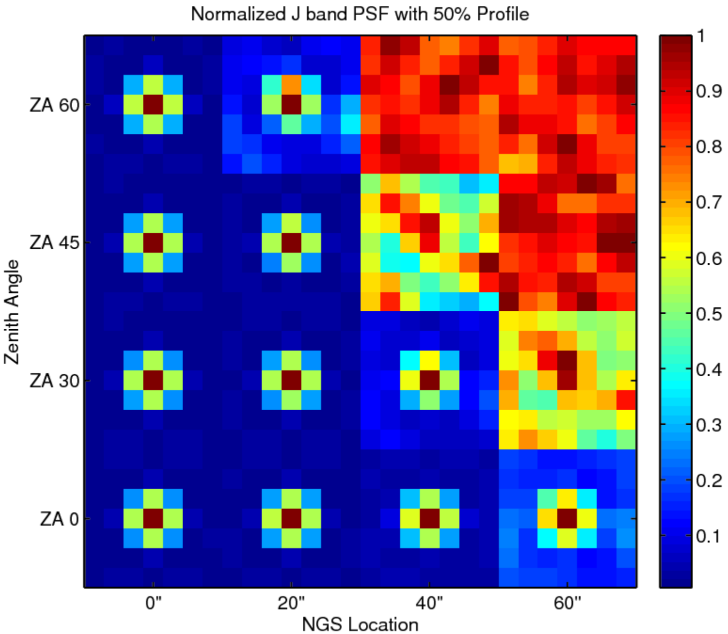
Estimated ensquared energy curves

50% Mauna Kea turbulence conditions

Sky Coverage Analysis

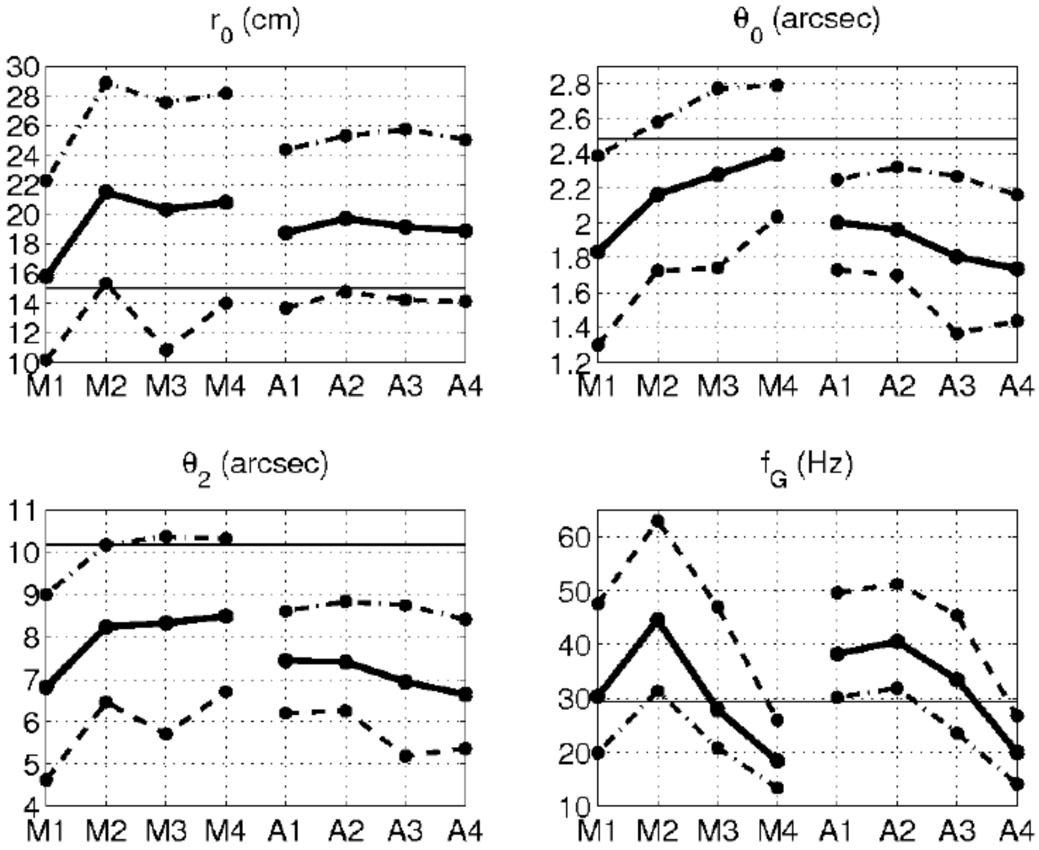
- Performance characteristics of H2RG OIWFS detector modeled in detail
- Matched filter pixel processing algorithms and type II woofer-tweeter control law have been tuned to optimize performance
- Requirements met with margin at zenith
- Off-zenith performance limited by physical optics effects
  - Lower NGS Strehls, smaller θ_0 and θ_2, no diffraction-limited PSF core at large offsets
  - Unobserved previously with geometrical OIWFS models excluding physical optics effects





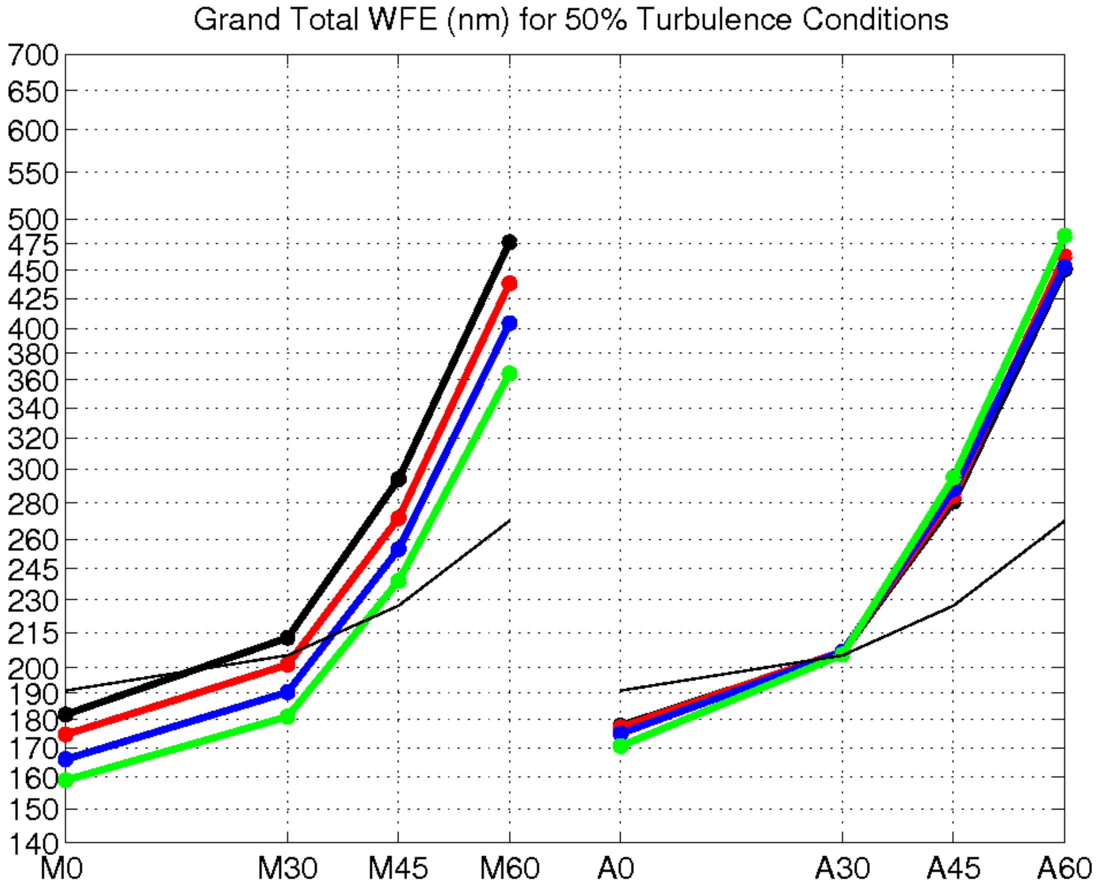
Performance vs seasons

- Turbulence spatio-temporal parameters versus seasons starting with winter (Dec.- Feb.), for Mauna Kea (M1-M4) and Cerro Armazones (A1-A4).
- At Zenith and λ= 500nm



RMS WFE (nm) versus zenith angle Mauna Kea and Cerro Armazones.

Black red blue green curves correspond respectively to the winter/spring/summer/fall seasons



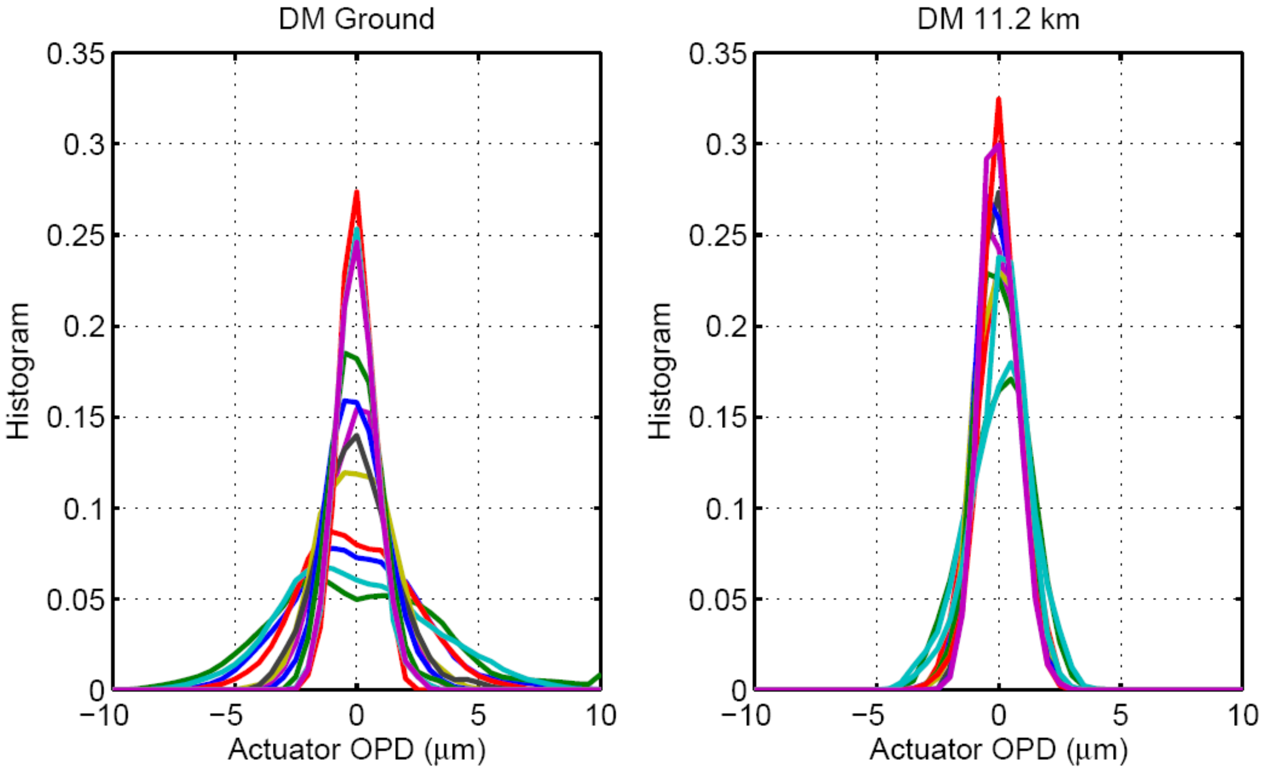
Mauna Kea C. Armazones

DM stroke requirements

- Histogram of the DM actuator commands
- OPDs of the ground and upper DMs for a variety of turbulence profiles that have similar 90th percentile θ_0
- But quite different values of r_0, ranging from 0.07 m to 0.193 m.
- The outer scale is 30 m.
- The upper DM has more or less similar command distributions for all of the profiles
- The ground-conjugate DM has broader histograms for smaller values of r_0.

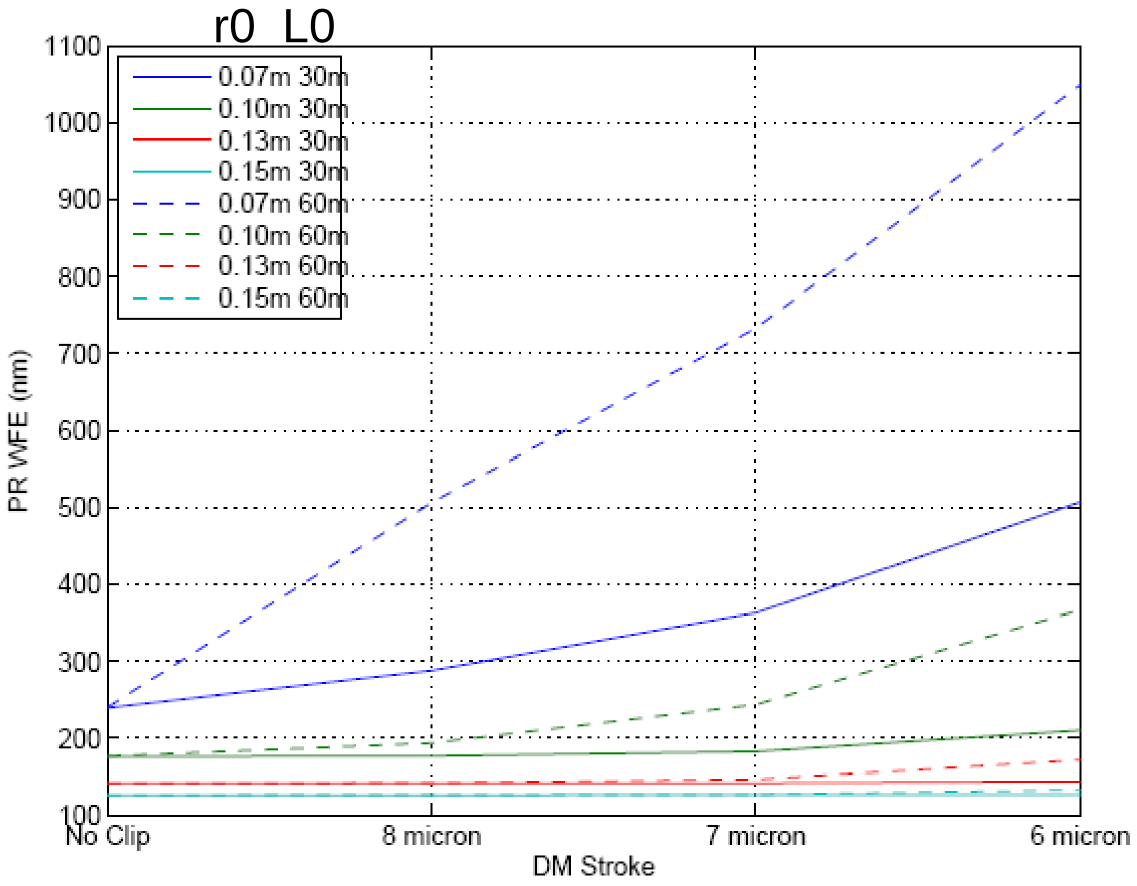
Deformable Mirror Stroke Requirement

Histograms of actuator commands



Wavefront Error vs DM stroke for Classic AO (single DM system)

L0 = {30, 60} m and r0 = {0.07, 0.1, 0.13, 0.15} m



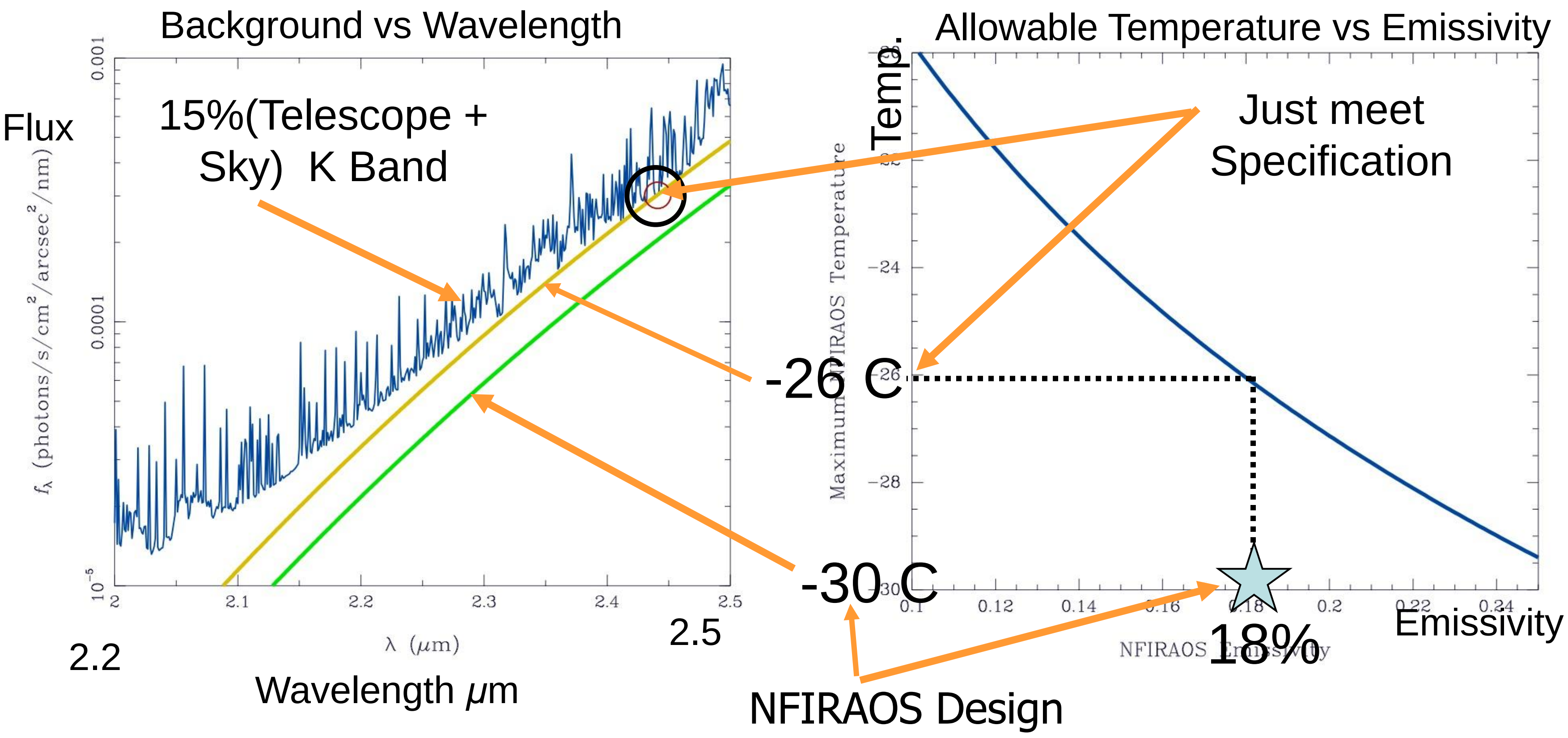
If L0 is large for a given r0, then DM requires more stroke to achieve the same wavefront same error

Site Survey Temperature Data

- Site survey data of mountain-top temperature drives AO system temperature for low background observations.
- Median Temperature on Mauna Kea is 2.3 C
- Requirement of NFIROAS adding < 15% of sky and telescope background in K band implies cooling NFIRAOS.

Temperature vs Emissivity

- Observing time decreases directly with decrease in thermal background
- Cooling NFIRAOS cuts observing time by a factor of 2.4 in K band



Background vs Wavelength

Allowable Temperature vs Emissivity

Flux

15%(Telescope + Sky) K Band

Just meet Specification

-26 C

-30 C

Temp.

2.2

2.5

Wavelength μm

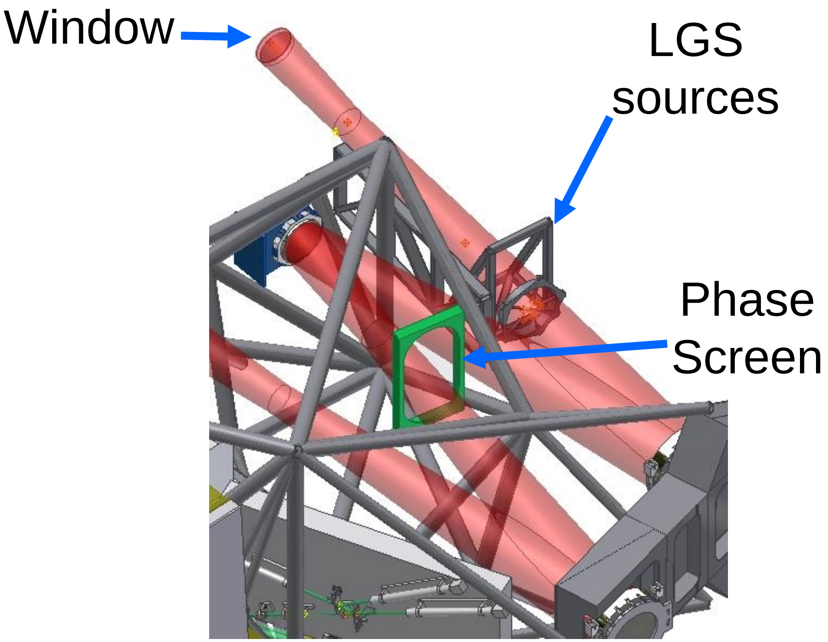
18%

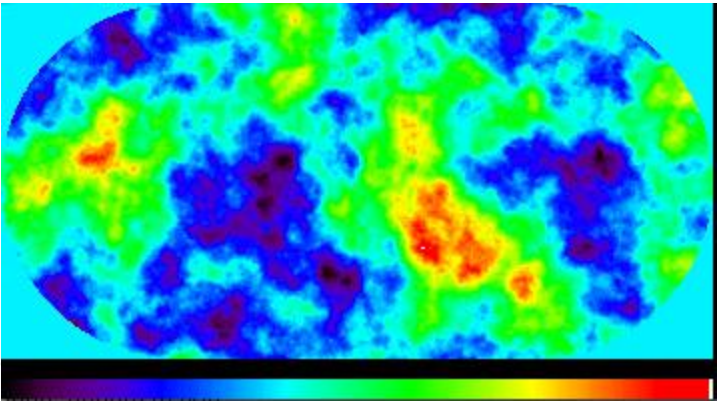
Emissivity

NFIRAOS Design

Turbulence Simulator

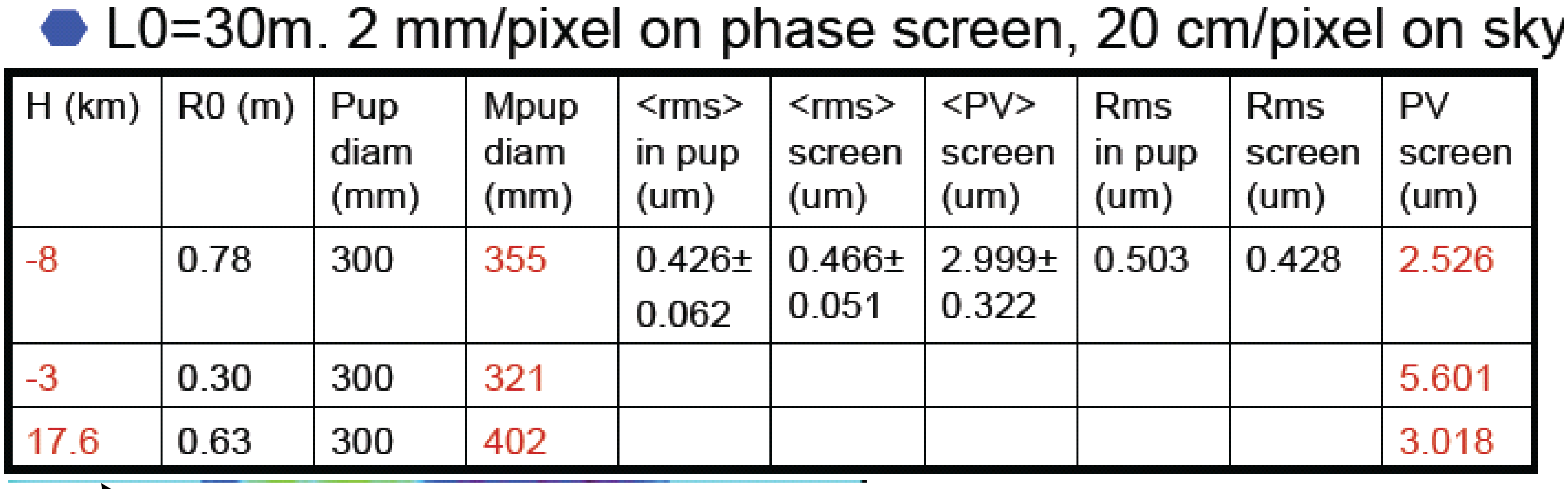
- Phase screen deployed into science path
- Eliminates separate turbulance simulator in front of window
- We are investigating MRF polishing of the phase screens ~ 360 x 750 mm
- Turbulence also added to DM commands
- Reproduces r_0 & θ_2





Turbulence Simulator screen

- Optimal altitude & strength of screen to build into AO system.
  - Estimated by simulations based on site survey data.

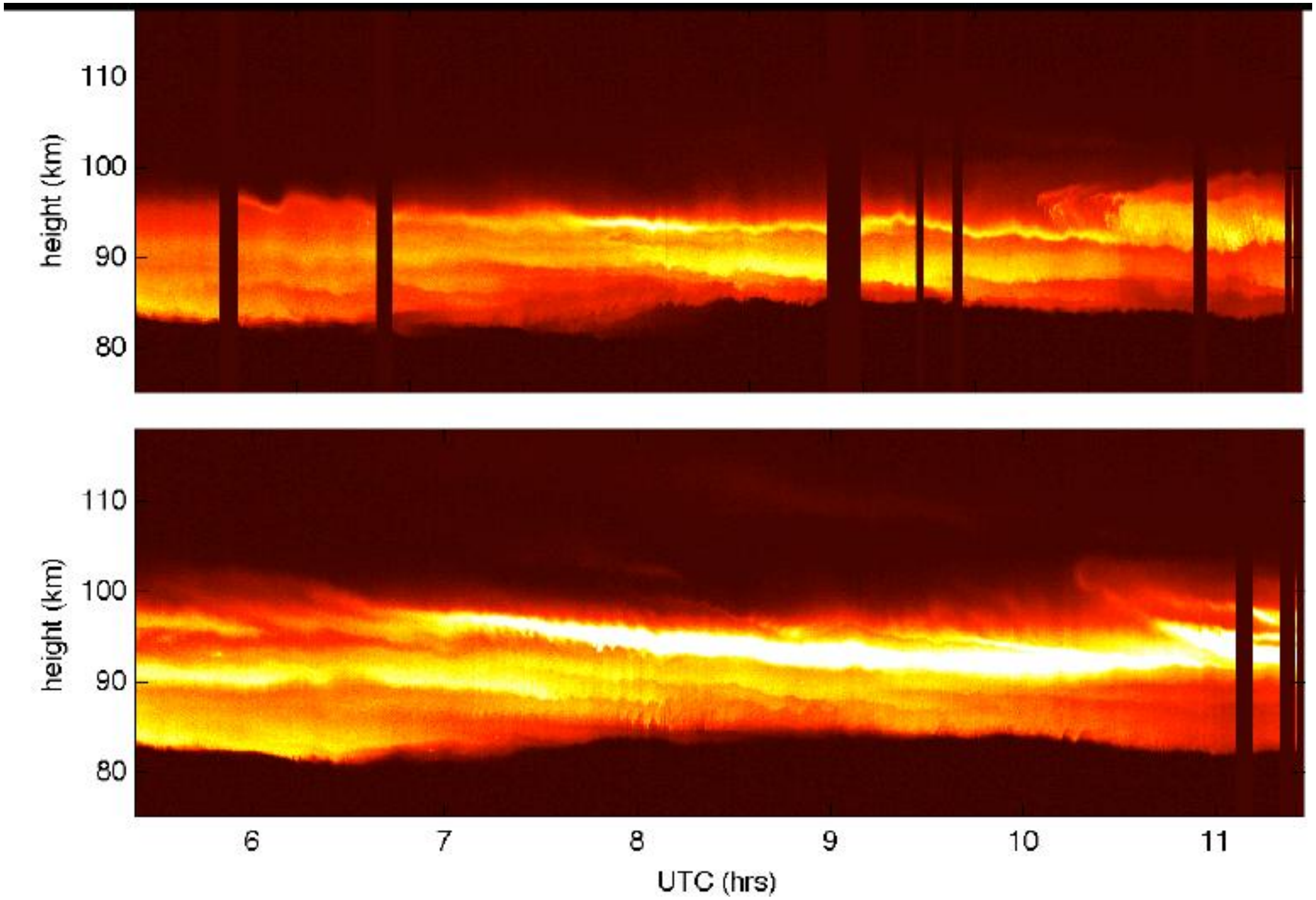


- L0=30m. 2 mm/pixel on phase screen, 20 cm/pixel on sky

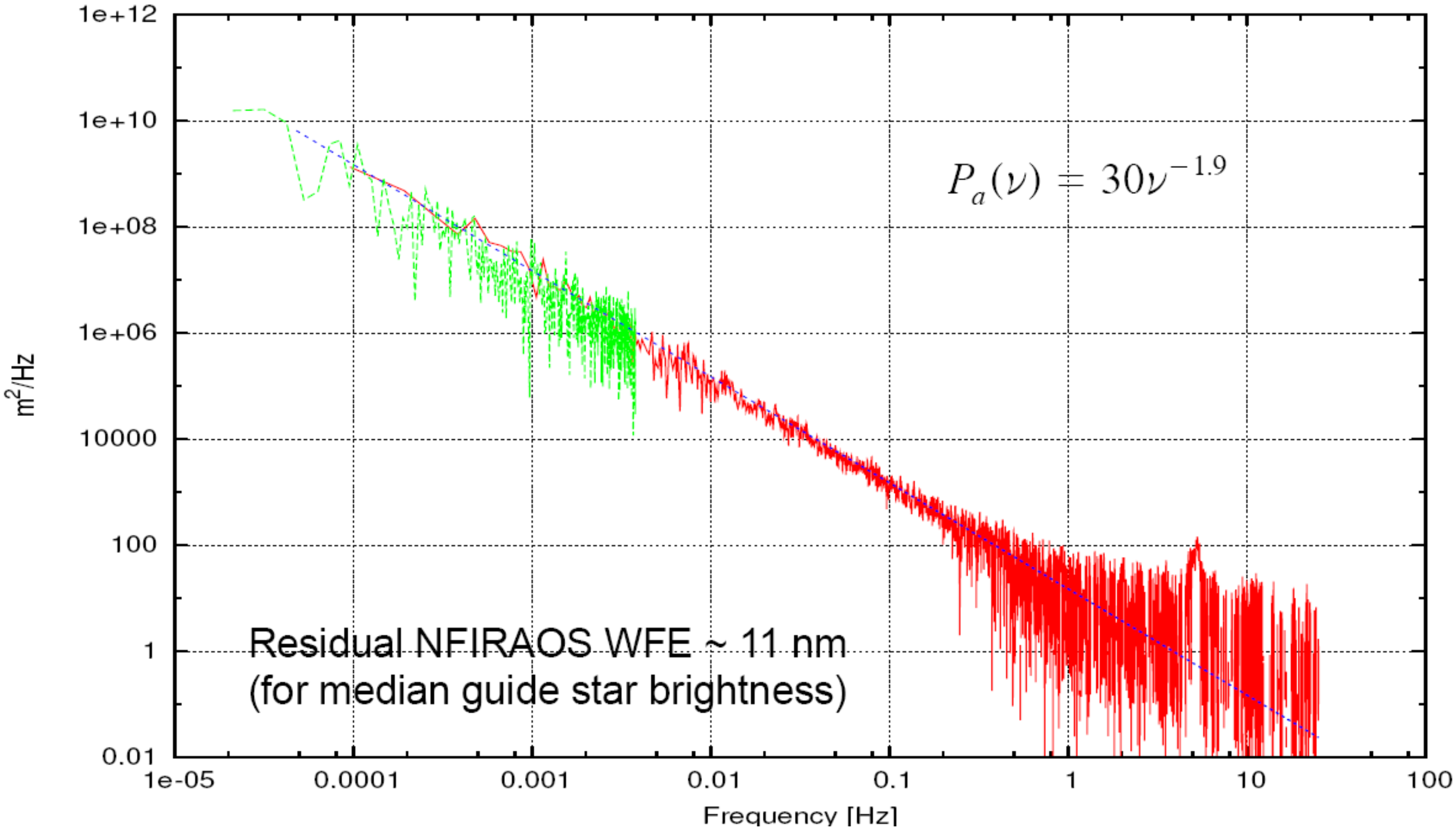
H (km)	R0 (m)	Pup diam (mm)	Mpup diam (mm)	<rms> in pup (um)	<rms> screen (um)	<PV> screen (um)	Rms in pup (um)	Rms screen (um)	PV screen (um)
-8	0.78	300	355	0.426± 0.062	0.466± 0.051	2.999± 0.322	0.503	0.428	2.526
-3	0.30	300	321						5.601
17.6	0.63	300	402						3.018

Candidate
Altitude

Sodium Density Profiles from UBC Vancouver Lidar

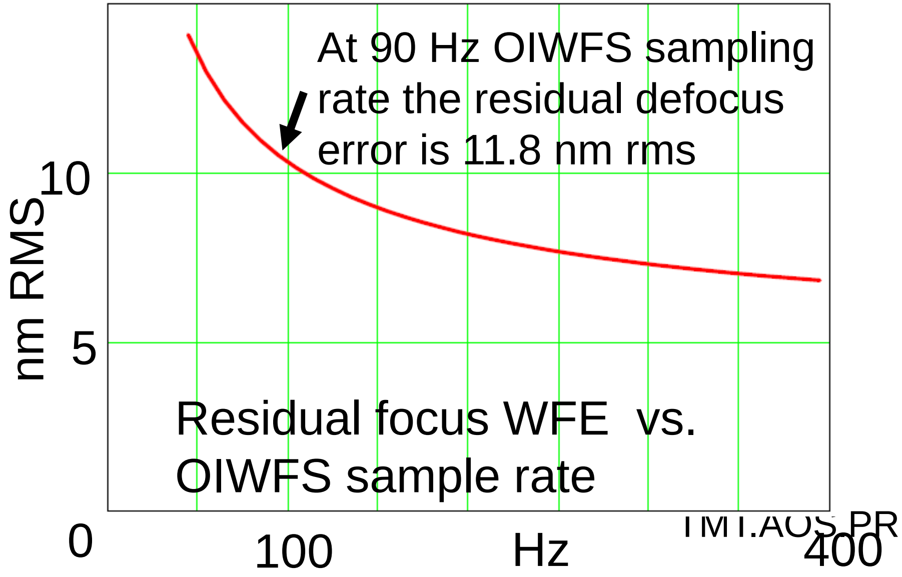


Power Spectrum of Sodium Altitude from UBC Lidar -



Na Layer Range Tracking

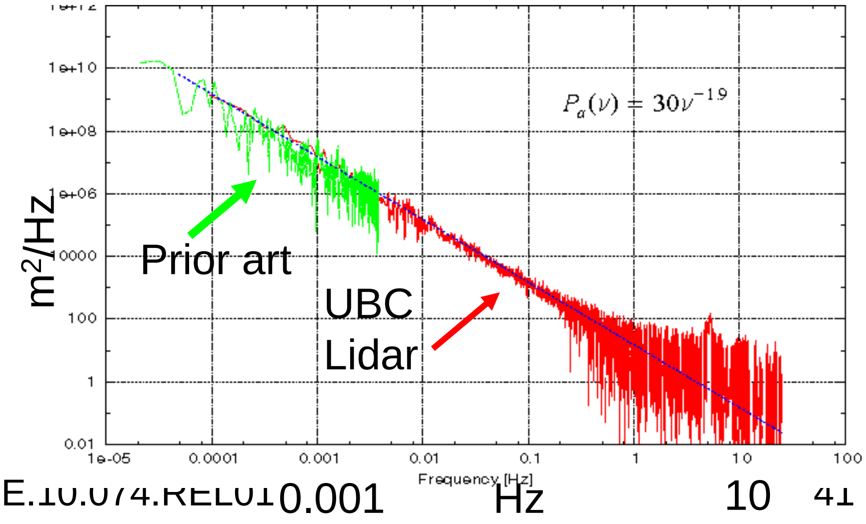
- Error in Na layer range is tracked by the OIWFS
  - 4 nm / meter of error in Na range estimation
- But OIWFS sampling frequency can be low (median 90Hz), so errors will occur due to delay
- Error budget updated via latest UBC Lidar measurements



At 90 Hz OIWFS sampling rate the residual defocus error is 11.8 nm rms

Residual focus WFE vs. OIWFS sample rate

Sodium altitude power spectrum

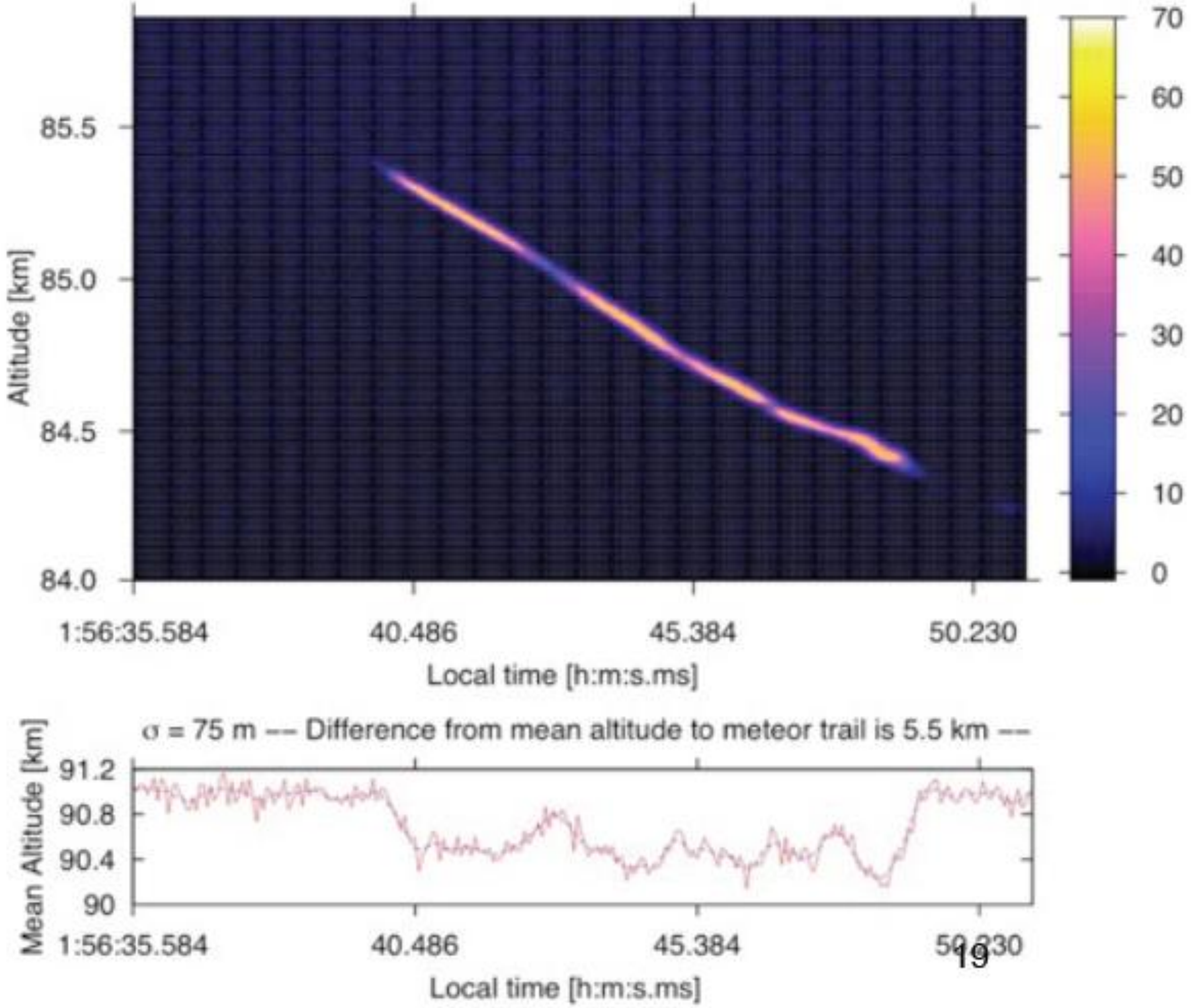


Prior art

UBC Lidar

Meteor Trails

- up to 1 km change in mean sodium altitude in ~ 1 sec. (4 um of rms wavefront error)
- typically 1 to 2 significant events per hour



Simulation results from Sodium data

- Sodium movies played into simulations, in computer and on UVic AO lab bench to assess:
  - Residual errors from meteor transients.
  - Power consumption of focusing trombone
    - 60 W during meteor transient (early result to be confirmed)
  - Determine suitable update interval for background tasks, and residual errors from sodium variability

Adaptive Vibration Compensation Algorithm

- Efficiently compensates for the effects of vibrations using a local oscillator locked in phase, amplitude and frequency that injects a counter vibration on TTS and tracks changing conditions.

Tip/Tilt residual (mas rms)

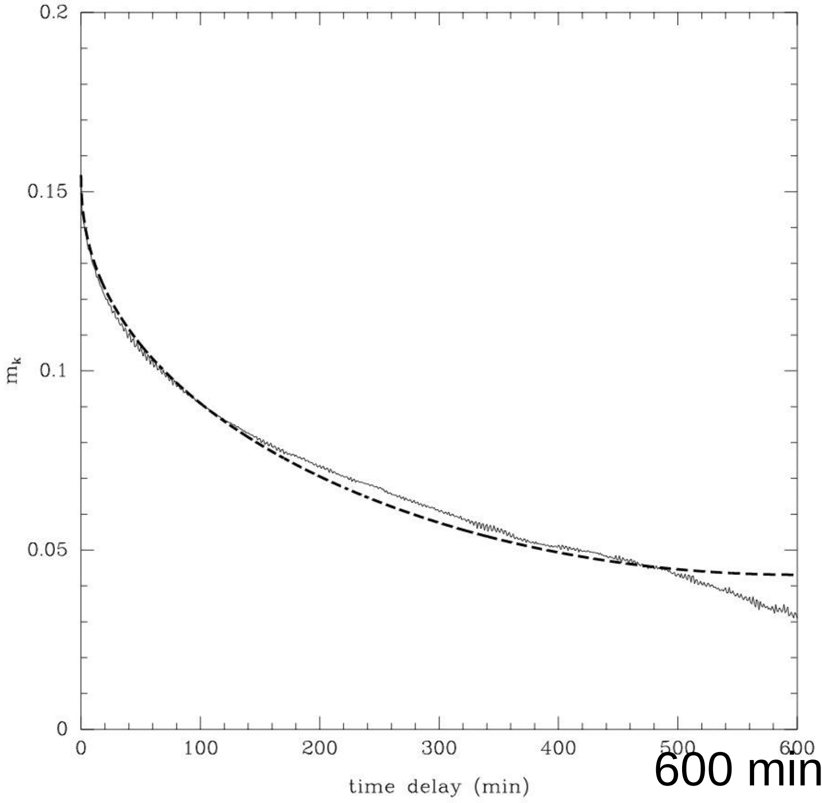
WFS freq / Control	800 Hz	90 Hz	40 Hz
Type I control	8.210	23.06	14.29
Type II control	8.810	21.30	14.30
Type II + Notch	2.944	15.51	14.30
Type II + AVCA	0.00434	0.0919	0.303

Input Tip/Tilt disturbance:
Atmosphere: r0=15cm, L0=30m
Windshake: 50%, rms=7.5mas
Total: 18.8mas rms
29.5Hz vibration: 13.3mas rms
Total disturbance: 23mas rms

- Offers superior performance and works even at low sampling frequencies of OIWFS (TT WFS)
- Performance is only reduced when WFS sampling frequency ~ vibration frequency due to aliasing

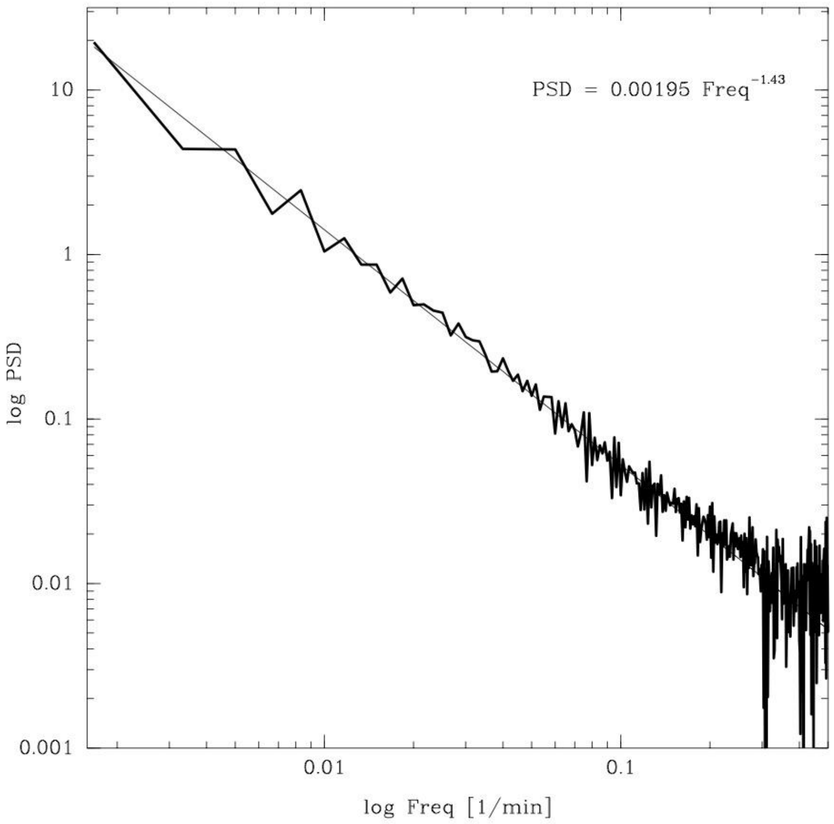
Time Variability of r_0

Autocorrelation of
log(r_0)

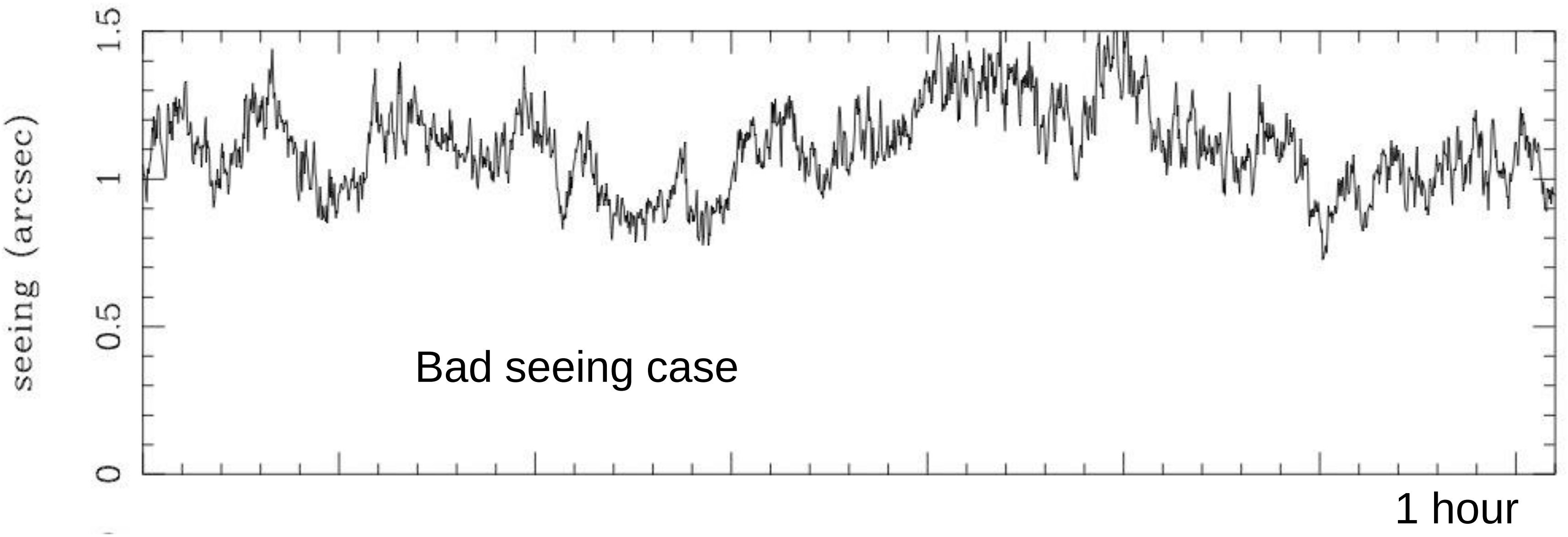


600 min

Power spectrum of log(r0)



r0 time series – autoregressive model built from autocorrelation of r0



Bad seeing case

- Avoids having to choose a “representative” night time series.
- Time series used in simulations of
  - NGS-mode WFS centroid gain estimator (background task)
  - image smearing during long exposures to assess astrometry accuracy.

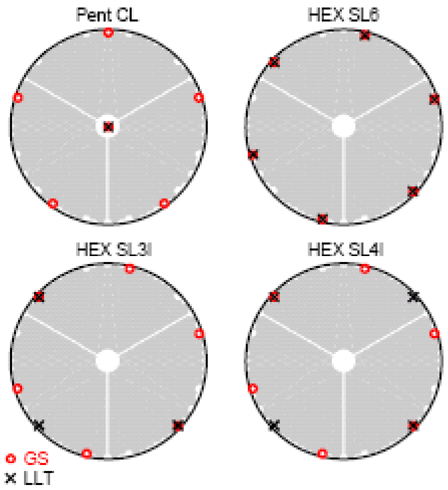
Desirable to have autoregressive model of the evolution of layers' strength

- Layers' strength vs time
  - Would like to assess importance of good initial guess of layer strength for tomography,
  - Would like to estimate update rate needed for background tasks
- However, the technique for r_0 just described does not work for individual layers of TMT site data.
  - too noisy per-layer TMT data.. negative numbers sometimes.

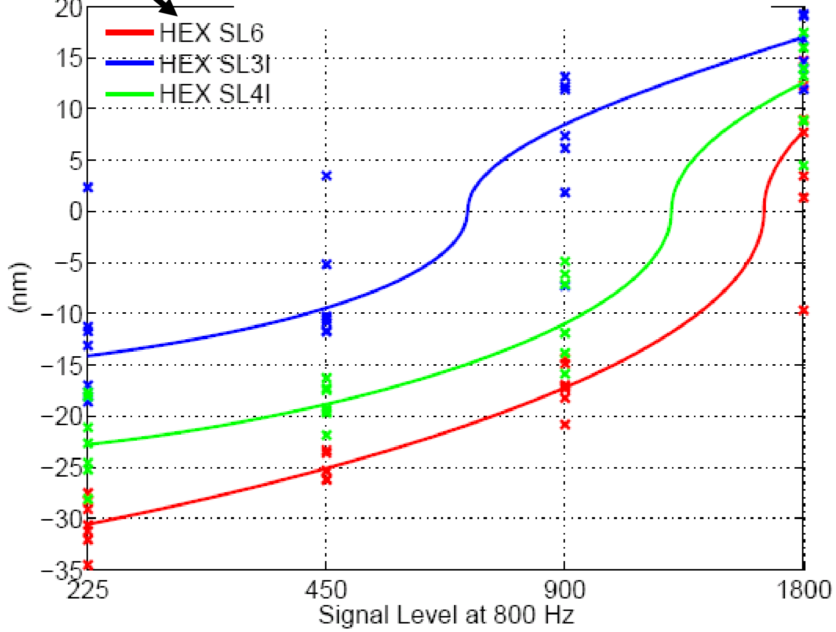
Laser Launch Telescope Location

- End to end Monte Carlo physical optics simulations
  - Side launch provides ~20 nm better Wavefront error, but at increased cost and complexity.
  - 4 laser launch telescope (LLT) configurations investigated.
  - Circles indicate the associated guide star (GS) asterism. Each GS is projected by the closest LLT, in all cases.

TMT Baseline



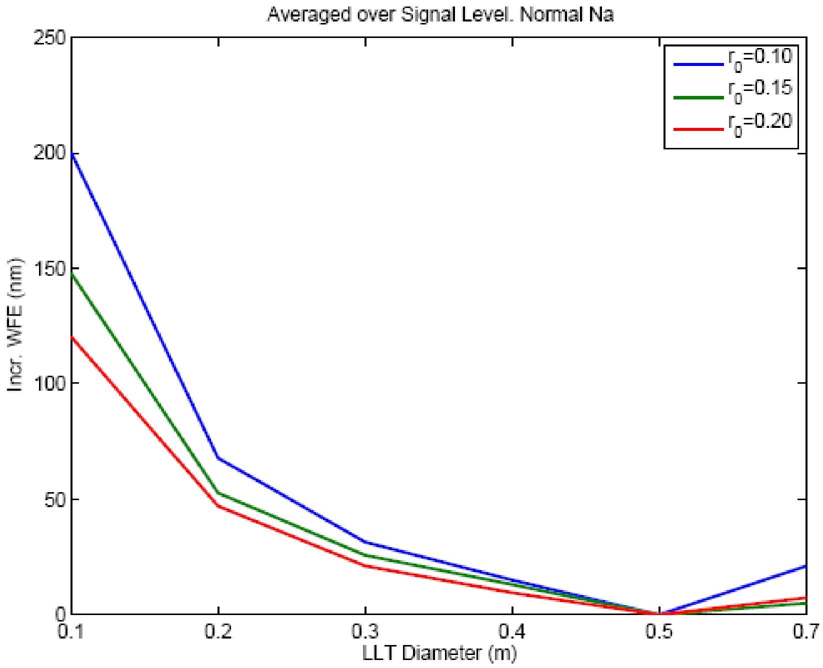
Incremental WFE w.r.t baseline



Laser Launch Telescope Diameter

- LLT diameters 0.1, 0.3, 0.4, 0.5 and 0.7 m,
- r0 0.10, 0.15, 0.20 m, { 75%, 50%, 25% } seeing,
- LGS signal levels of 250, 500, and 1000 photons detected /subaperture/frame at 800Hz,
- Nominal sodium profile
- Nominal Cn^2 profile for Mauna Kea

Incremental Wavefront error vs Launch telescope Diameter



Acknowledgements

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