Keck Adaptive Optics Note 504

NGAO Performance vs. Technical Field of View for LOWFS Guide Stars

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1. Introduction

The NGAO System Architecture Retreat, July 9-13, 2007, raised several questions regarding the technical field of view requirements for NGAO. The purpose of this note is to understand the performance compromises for NGAO that arise when limiting the technical field of view.

2. Technical Field of View (TFoV)

We define the TFoV as the field of regard on the sky from which the set of NGAO low-order guide stars can be simultaneously acquired into the low-order wavefront sensor (LOWFS) system, which typically uses natural guide stars to determine wavefront tilt not available in the laser guide star (LGS) high-order wavefront sensor (HOWFS) subsystem and to repair errors in the tomographic null modes arising in our multi-LGS HOWFS.

All fields of view in this note are circular diameters, assumed to be centered on the science target, in the direction of which the LGS asterism is formed by the LGS beam delivery system.

3. LOWFS Sharpening in J + H

We assume IR LOWFS stars are sharpened to (nearly) the diffraction limit by high-order MEMS-based DM's within each LOWFS sensor, using go-to control techniques characteristic of the Multi-Object AO (MOAO) paradigm. (Typical correction of the off-axis LOWFS stars in this study, while not checked exhaustively, is typically in the J-Strehl ~ 50% range. Even though the LOWFS are quite a distance off-axis, the error budget optimization allows the LGS asterism to be widened to continue to correct these off-axis stars (albeit with increasing tomography error).

An alternative approach to off-axis LOWFS sharpening, being considered, is to dedicate a sodium LGS to each LOWFS star, thus allowing the 'science LGS asterism' to not be pulled to so large a radius as is typically found in this study. Although the relative merits of a large LGS asterism or a 'point-and-shoot' LOWFS sharpening system remains uncertain, we assume here that the same LOWFS sharpening can be obtained in either scenario, so these results remain essential valid (as they, in fact, must if NGAO is to generally meet it's science requirements of very high on-axis near-IR Strehl ratio.)

Continued next page.

4. Model assumptions

These calculations have been conducted using v1.31 of the NGAO Wavefront Error (WFE) Budget Tool[1], adopting:

<u>Atmosphere</u>

Mauna Kea Ridge[2] (MKR) "Median" 50^{th} percentile seeing conditions
(r_0 = 16 cm, θ_0 = 2.7 arcsec, d_0 = 4.85 m, all at λ = 0.5 μm)

or Mauna Kea Ridge (MKR) "Excellent" 87.5^{th} percentile seeing conditions
(r_0 = 22 cm, θ_0 = 4.0 arcsec, d_0 = 7.33 m, all at λ = 0.5 μm)

Average turbulence-weighted wind speed of 9.5 m/s (with f_G = 28.0 Hz)
Outer scale = 50 meters

<u>HOWFS</u>

6 LGS in a "5+1" asterism geometry (of variable radius)
and 3 LGS that are 'Roving' and point slightly away (radially outward) of each LOWGS NGS
A total of 120W of SOR CW laser-like return (1902 ph/cm^2/sec for each 20W (spigot) laser)
T = 0.75 transmission on uplink
4e9 /cm^2 Na layer column density abundance
T = 0.26 transmission on downlink (0.85 atm x 0.31 optics)
$FWHM_{LGS\ in\ SH\ subaperture}$ = 1.63 arcsec (center projected, avg. elongation)
64 x 64 subapertures for all 6 science-pointed LGS HOWFS
32 x 32 subapertures for 3 roving LGS HOWFS[3]
CCID56 WFS detector with 2.2 e- read noise at ~1600 fps frame rate

<u>LOWFS</u>

3 NGS stars corrected using the MOAO technique (LOWFS m_V refers to the brightest NGS)
2 TT + 1 TTFA (on brightest star)
32 x 32 MEMS correction in LOWFS channels
M-type NGS
J+H LOWFS sensing bands
T = 0.24 transmission on downlink
Perfect K (and other) band rejection
H2RG in ROI mode readout
4.5 e- read noise at ~700 fps (quad-cell) frame rate
0.05 x 0.05 arcsec / pixel (0.1 x 0.1 arcsec subap for background sky calc)
'Point and Shoot[4]' wavefront sensing of the LOWFS stars (e.g. a roving LGS pointing 11arcsec radially outside of each LOWFS NGS)
Uses tomography error for TT stars internal to LGS asterism

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[1] Compared to the original version of this KAON, which used v1.26 of the WFE Budget Tool, we have change the seeing model to correspond to 50^{th} percentile conditions, corrected two Tool bugs (one underestimated N_stars per square arcmin, the other erroneously applied chromatic dispersion to LGS HOWFS spot size), and improved the off-axis TT star Strehl model (for example, to only use N=32 actuators in the TT MOAO MEMS mirrors.)

[2] See KAON #504, Version 1.1 for more information on these $C_n^2(h)$ models.

[3] This is not a particularly important choice – if use of 9 identical HOWFS were cost effective, there would be little impact on the amount of laser power required for the roving LGS's.

[4] The 'Point and Shoot' strategy use tomographic wavefront sensing information from both the on-axis science LGS asterism and (one or more) roving LGS beacons, pointed near, but somewhat further outside (radially) , the LOWFS stars. This allows the roving LGS to sample a larger fraction of the missing conical wavefront seen by downpropagating LOWFS NGS starlight. The optimal location for the 'Point and Shoot' LGS have not been determined.

Plus, MIN(classical anisoplanatism error for the angle outside of LGS asterism, FA error from the roving LGS alone.)

Target

Faint compact source science program (such as KBO observations)
Zenith angle = 18 degrees
300 second exposure (with 0.75 mas / min total mechanical drift = 3.75 mas fixed tip/tilt error)
Science band ADC (but no ADC in the LOWFS)
Single-conjugate AO science correction
Science evaluation at off-axis evaluation angle = 5.0 arcsec

5. Results

The summary of our trade study, for two different atmospheric models is shown in Figure 1 (with supporting values in the Appendix).

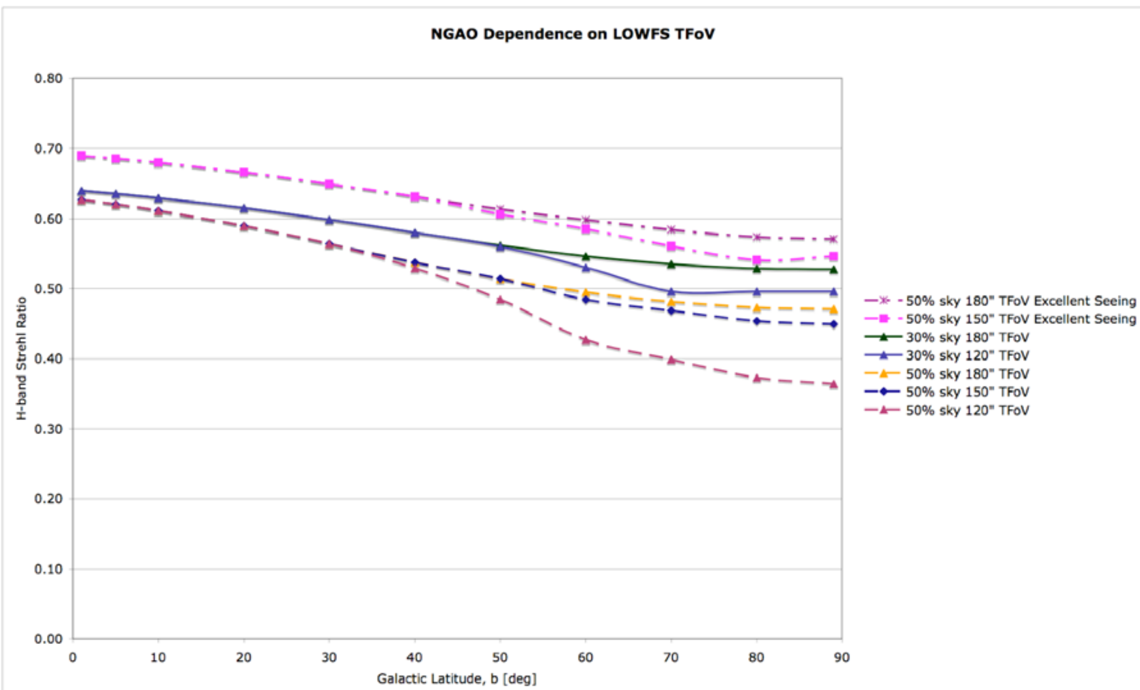

Figure 1. Summary of TFoV trade study, showing the deleterious impact of 120" TFoV. Based on these analyses this KAON recommends a LOWFS TFoV = 150" (diameter).

Figure 1 is interpreted as the H-band Strehl ratio performance vs. galactic latitude under our assumptions, when the TFoV are limited to certain radii. We see that for 50% sky fraction and 120" TFoV, performance is degraded above b ~ 40 degrees. Similarly, for 30% sky fraction and 120" TFoV, performance is degraded above b ~ 60 degrees. Thus, we believe that 120" TFoV is insufficient and unduly impacts performance.

Exploring 150" TFoV, we see that for 30% sky fraction, there is only a small compromise, coming above b ~ 60, and never worse than a reduction in H-Strehl from ~47% to 45%. In excellent seeing conditions (top curves), the 150" TFoV degrades performance beyond b ~ 50, but the absolute effect is similar, reducing 57% H-Strehl to ~55%.

[In fact, we find that even 180” TFoV imposes an artificial limit above b = 70 degrees for 50% sky fraction, but the effect on performance appears to be rather minor.]

A similar curve for H-band ensquared energy is shown in Figure 2, for median conditions, and the following major difference:

<u>Target</u>

Extended Groth Strip science case
Zenith angle = 34 deg
Off-axis evaluation angle = 1.5 arcsec

In this case, assuming a deployable IFU instrument and performance specification given on a 70 x 70 milliarcsec spaxel, we can tolerate larger tip/tilt errors. Thus, ensquared energy loss is not nearly as dramatic for TFoV is limited to 120”.

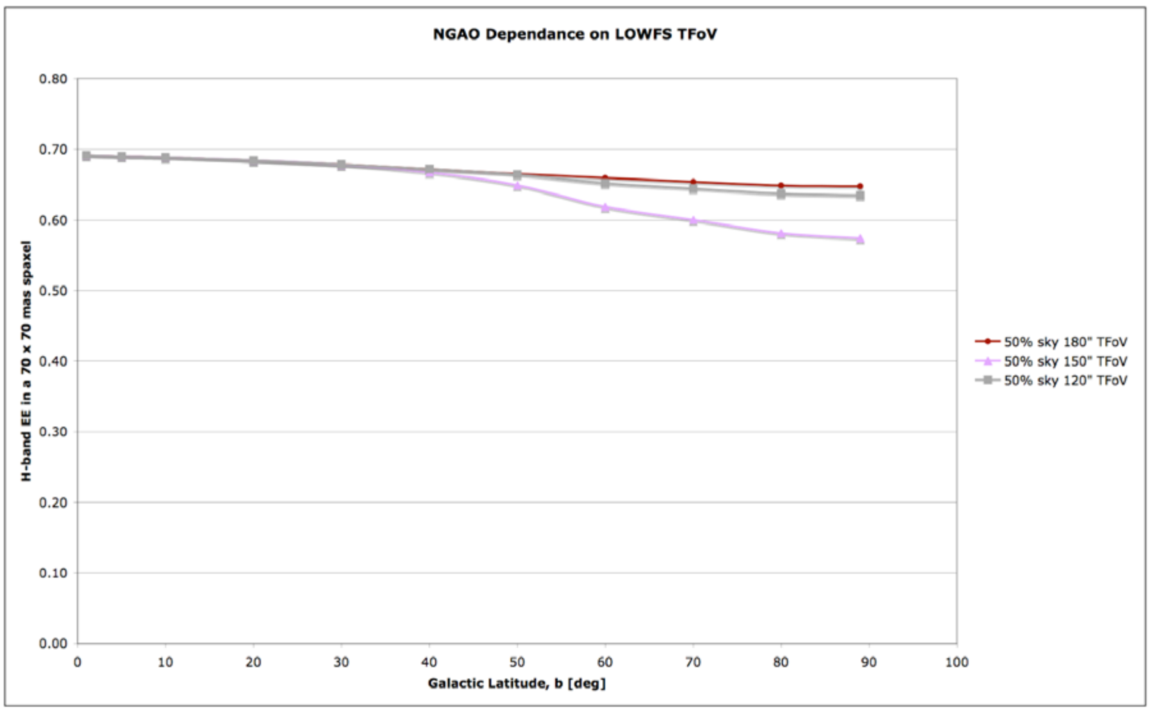

Figure 2. Ensquared Energy for the Extended Groth Strip science case, for different b.

6. Acquisition Efficiency

As NGS become fainter, they will require more time to acquire into the NGAO LOWFS subsystem. It is therefore not entirely equitable to reduce the NGS brightness to whatever faintness is necessary to meet the 30% sky coverage specification. Although point source sensitivities were not, as of this writing available, we presume that acquisition of NGS fainter than $m_H = 18.0$ ($m_V = 21.5$) will be objectionable time-consuming. In the Appendix, we highlight these situations with red background.

7. Comparison to KAON 470

KAON 470, “Keck NGAO sky coverage modeling” by Richard Clare reached a conclusion that 120” TFoV was sufficient, based on certain assumptions. In particular, this KAON concluded that “A 2 arc min diameter patrol field for finding NGS is sufficient, there is little benefit to making the field larger due to the reduced partial correction and tilt anisoplanatism from being so far off-axis.” However, an assumption of KAON 470 was having a fixed LGS asterism radius. To quote, “…this calculation did not take into account the optimization of the LGS asterism radius for each NGS constellation – a radius of 21.6 [arcsec] was assumed throughout."

In the current work, we use a more sophisticated model for how 'Point and Shoot' MOAO can be used to correct for off-axis LOWFS NGS's. The result is that we maintain relatively high LOWFS star Strehl ratio out to larger off-axis distances, improving the net AO science correction when using these off-axis stars. Thus, this work argues for a larger TFoV than recommended in KAON 470.

We find that for the Mauna Kea Ridge "median" 50th percentile seeing condition, that a technical field of view of 150" (diameter) appears sufficient. This conclusion differs from the 180" TFoV conclusion in Version 1.0 of this KAON because 1) the 50th percentile conditions are worse than the 62.5th percentile previously used – this reduces the utility of far-off-axis LOWFS NGS; 2) a more sophisticated model for LOWFS NGS Strehl ratio has been incorporated to approximate the correction expected with the 'Point and Shoot' wavefront sensing strategy; and 3) several (largely offsetting) bugs in the WFE budget tool have been corrected.

Correspondingly, the 'Point and Shoot' strategy requires an LGS TFoV that is approximately 12 arcsec greater in radius than the LOWFS TFoV, resulting in an LGS TFoV of 150 + 2*12 = 174 arcsec diameter[5]. In other words, LGS placed within a 174 arcsec diameter circle, centered on the science target, should be passed by the NGAO optical system without vignetting.

[5] Note, the LOWFS TFoV and LGS TFoV are defined for different conjugate locations (90 km vs. ∞, respectively).

8. Conclusions

Based on this analysis, we conclude that science performance would be significantly impacted with a LOWFS TFoV of only 120 arcsec for galactic latitude greater than b = 40 in median NGAO seeing conditions. Extended Groth Strip $EE_{70\ mas}$ for example would be degraded by about 10% (absolute) compared to 150 arcsec TFoV.

A TFoV of 150 arcsec allows selection of the optimally selected combination of NGS off-axis distance and brightness, under the assumptions stated above, and is recommended. The corresponding LGS TFoV for the 'Point and Shoot' sensing strategy should therefore be 174 arcsec.

Appendix

The following tabular values were produced for this study (continued next page):

180 TFoV **50% sky**
120W **excellent conditions**
N=64

	Ast R arcmi	WFE (nm)	SR_H	TT search arcsec	TT mag mH	EE_70mas H-band	TT Error (mas)
1	0.11	159	0.69	35.8	13.92	0.76	4.74
5	0.11	160	0.69	39.3	14.00	0.76	4.86
10	0.11	162	0.68	43.8	14.11	0.76	5.05
20	0.11	166	0.67	53.7	14.30	0.76	5.47
30	0.11	171	0.65	63.9	14.49	0.76	5.97
40	0.11	176	0.63	74.1	14.64	0.75	6.49
50	0.11	182	0.61	83.5	14.77	0.75	7.00
60	0.11	187	0.60	89.9	14.92	0.75	7.43
70	0.11	191	0.58	90.0	15.20	0.74	7.82
80	0.11	194	0.57	90.0	15.35	0.74	8.11
89	0.11	195	0.57	90.0	15.39	0.74	8.18

150 TFoV **50% sky**
120W **excellent conditions**
N=64

Ast Radius arcmin	WFE (nm)		SR_H	TT sear arcsec	TT mag mH	EE_70n H-band	TT Error (mas)
1	0.11	159	0.69	35.8	13.92	0.76	4.74
5	0.11	160	0.69	39.3	14.00	0.76	4.86
10	0.11	162	0.68	43.8	14.11	0.76	5.05
20	0.11	166	0.67	53.7	14.30	0.76	5.47
30	0.11	171	0.65	63.7	14.50	0.76	5.97
40	0.11	177	0.63	74.0	14.65	0.75	6.49
50	0.11	184	0.61	75.0	15.14	0.75	7.20
60	0.11	190	0.59	75.0	15.57	0.75	7.78
70	0.11	198	0.56	75.0	15.87	0.74	8.47
80	0.11	204	0.54	75.0	16.05	0.74	9.02
89	0.11	202	0.55	75.0	16.09	0.74	8.87

180 TFoV **30% sky**
120W
N=64

	Ast R arcmi	WFE (nm)	SR_H	TT search arcsec	TT mag mH	EE_70mas H-band	TT Error (mas)
1	0.10	174	0.64	27.5	13.75	0.71	5.03
5	0.10	175	0.64	30.1	13.83	0.71	5.16
10	0.10	177	0.63	33.5	13.94	0.71	5.36
20	0.10	181	0.62	41.0	14.12	0.71	5.82
30	0.10	187	0.60	48.6	14.31	0.71	6.35
40	0.10	192	0.58	56.5	14.44	0.70	6.90
50	0.10	198	0.56	63.4	14.58	0.70	7.44
60	0.10	202	0.55	68.1	14.73	0.70	7.90
70	0.10	206	0.54	71.3	14.84	0.70	8.23
80	0.10	208	0.53	75.0	14.82	0.69	8.42
89	0.10	208	0.53	75.0	14.84	0.69	8.45

120 TFc **30% sky**
120W
N=64

	Ast Rad arcmin	WFE (nm)	SR_H	TT searc arcsec	TT mag mH	EE_70mas H-band	TT Error (mas)
1	0.10	174	0.64	27.5	13.74	0.71	5.03
5	0.10	175	0.64	30.1	13.83	0.71	5.16
10	0.10	177	0.63	33.5	13.94	0.71	5.36
20	0.10	181	0.62	41.0	14.12	0.71	5.82
30	0.10	187	0.60	48.6	14.31	0.71	6.35
40	0.10	192	0.58	56.4	14.45	0.70	6.90
50	0.10	198	0.56	60.0	14.76	0.70	7.49
60	0.10	207	0.53	60.0	15.17	0.69	8.37
70	0.10	218	0.50	60.0	15.46	0.69	9.40
80	0.10	218	0.50	60.0	15.46	0.69	9.40
89	0.10	218	0.50	60.0	15.46	0.69	9.40

180 TFoV **50% sky**
120W
N=64

	Ast R arcmi	WFE (nm)	SR_H	TT search arcsec	TT mag mH	EE_70mas H-band	TT Error (mas) 89.00
1	0.10	178	0.63	34.6	14.01	0.71	5.45
5	0.10	180	0.62	37.9	14.10	0.71	5.66
10	0.10	183	0.61	42.4	14.21	0.71	5.94
20	0.10	189	0.59	52.0	14.40	0.70	6.61
30	0.10	197	0.56	62.1	14.58	0.70	7.37
40	0.10	205	0.54	70.3	14.82	0.70	8.15
50	0.10	212	0.51	77.5	15.02	0.69	8.85
60	0.10	218	0.49	83.9	15.16	0.69	9.42
70	0.10	223	0.48	88.5	15.26	0.68	9.84
80	0.10	225	0.47	90.0	15.35	0.68	10.09
89	0.10	226	0.47	90.0	15.39	0.68	10.15

150 TFoV **50% sky**
120W
N=64

Ast Radius arcmin	WFE (nm)		SR_H	TT sear arcsec	TT mag mH	EE_70n H-band	TT Error (mas)
1	0.10	178	0.63	34.6	14.01	0.71	5.45
5	0.10	180	0.62	37.9	14.10	0.71	5.66
10	0.10	183	0.61	42.4	14.21	0.71	5.94
20	0.10	189	0.59	52.0	14.40	0.70	6.61
30	0.10	197	0.56	62.1	14.58	0.70	7.37
40	0.10	205	0.54	72.1	14.73	0.70	8.16
50	0.10	212	0.51	75.0	15.14	0.69	8.84
60	0.10	222	0.48	75.0	15.57	0.68	9.74
70	0.10	227	0.47	75.0	15.87	0.68	10.22
80	0.10	231	0.45	75.0	16.05	0.67	10.69
89	0.10	233	0.45	75.0	16.09	0.67	10.82

120 TFc **50% sky**
120W
N=64

	Ast Rad arcmin	WFE (nm)	SR_H	TT searc arcsec	TT mag mH	EE_70mas H-band	TT Error (mas)
1	0.10	178	0.63	34.6	14.01	0.71	5.45
5	0.10	180	0.62	37.9	14.10	0.71	5.66
10	0.10	183	0.61	42.4	14.21	0.71	5.94
20	0.10	189	0.59	52.0	14.40	0.70	6.61
30	0.10	197	0.56	60.0	14.69	0.70	7.38
40	0.10	208	0.53	60.0	15.37	0.69	8.41
50	0.10	221	0.48	60.0	15.96	0.68	9.74
60	0.10	240	0.43	60.0	16.43	0.67	11.56
70	0.10	249	0.40	60.0	16.78	0.65	12.50
80	0.10	258	0.37	60.0	16.97	0.64	13.44
89	0.10	262	0.36	60.0	17.03	0.64	13.77