Keck Adaptive Optics Note 503

Mauna Kea Ridge (MKR) Turbulence Models

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1. Introduction

Recently, R. Flicker published an update the on-going site monitoring campaign undertaken at the 13N site on the north shield of Mauna Kea. This data set represents arguably, the most extensive investigation of conditions at any location on Mauna Kea ever conducted.

The Next Generation Adaptive Optics (NGAO) program wishes to incorporate the best understanding of actual conditions to be encountered by NGAO upon commissioning at Keck Observatory and therefore wishes to take advantage of the 13N data (and accompanying goodwill of the Thirty Meter Telescope Observatory, which has sponsored the so-called T6 telescope campaign at 13N.)

We proceed under the assumption that the ground-layer turbulence contribution at the 13N site is not representative of the conditions on the Mauna Kea ridge, but are a good representation of the upper-level turbulence (500 meter above ground and higher).

This note is intended to integrate the latest upgrade to upper atmosphere turbulence statistics into a set of new NGAO baseline atmospheric turbulence models consistent with the best understanding of overall seeing at the Keck Observatory site on the Mauna Kea ridge.

2. Preliminary comments on observing model

The NGAO program faces the same challenge as all astronomical adaptive optics systems when determining the atmospheric conditions for which to design. Use of overly optimistic turbulence models result can result in disappointing performance while overly conservative models can distort the systems engineering priorities causing certain subsystems to be over-specified relative to subsystems that ultimate limit AO system performance.

The initial approach of the NGAO team was to adopt a working model for Keck Observatory NGAO operations in which NGAO observations are not expected to be conducted in all atmospheric conditions. Specifically, we suppose that in the worst 25% of measured atmospheric conditions, NGAO observations would not be attempted (or perhaps NGAO LGS operations would not be attempted, their error budgets depending more sensitively to degradations of the seeing conditions.) Thus, we advocated that ‘practical median conditions’ seen by the NGAO system in operation to correspond to the median of the upper 75% of conditions during which NGAO observations would actually be scheduled. In practice, this would have resulted in a choice of the 62.5th percentile (slightly better than true median) conditions as our effective NGAO median conditions. (Since we will typically reference atmospheric statistics only collected during observable conditions, this choice is more strictly the 62.5th percentile of those nights not lost to inclement weather. Note, conditions of cirrus cloud cover *are* included to the extent that seeing monitor statistics include data obtained in at least moderate- cirrus conditions.)

However, our science user community was uncomfortable with this direction[1]. We therefore have revised this KAON to include the actually measured 'median' (50th percentile) conditions as best we understand them on the Mauna Kea Ridge, recognizing that design of the NGAO system to meet performance specifications at these less favorable conditions will drive up system cost and complexity.

Although we have therefore settled on true median conditions for our design criterion, we still recognize the need for some science cases and detailed observing model planning to consider a range of turbulence conditions, we extend this rationale to select the 37.5th, 62.5th and 87.5th percentile conditions as the NGAO "challenging", "good", and "excellent" seeing conditions respectively. Thus, these models bound 2/3 of the NGAO conditions expected to be encountered by NGAO observers[2].

3. Model development process

3.1 Integrated seeing conditions

KAON 303 (C. Neyman), and KAON 415 (R. Flicker, distribution restricted) provided earlier descriptions of seeing and $C_n^2(h)$ statistics recorded on Mauna Kea. KAON 415 was updated in KAON 496 (R. Flicker) to reflect the latest statistics recorded by the TMTO MASS/DIMM equipment operating at 13N. From these, we construct new $C_n^2(h)$ models (Section 3.2) and select corresponding r_0 values. Table 2 and Figure 3 of KAON 303 summarize statistics for the overall seeing on the Mauna Kea ridge.

Based on these data, recognizing the uncertainties in the absolute accuracy of these limited measurement campaigns, while desiring a convenient but traceable estimate for NGAO seeing conditions, we hereby adopt the following Mauna Kea Ridge (MKR) models:

MKR seeing condition	r_0 (λ = 0.5 um)	θ_0 (λ = 0.5 um)	$d_{0,\ 90\ km}$ (λ = 0.5 um)	Percentile seeing
"Excellent"	22.0 cm	4.00 arcsec	7.33 m	87.5th
"Good"	18.0 cm	2.90 arcsec	5.24 m	62.5th
"Median[3]"	**16.0 cm**	**2.70 arcsec**	**4.85 m**	**50.0th**
"Challenging"	14.0 cm	2.15 arcsec	3.83 m	37.5th

Table 1. NGAO seeing condition assumptions at zenith, where r_0 is Fried's parameter[4], θ_0 is the isoplanatic angle[5], and d_0 is the focal anisoplanatism coherence parameter.

Note, our use of r_0 = 16 cm and θ_0 = 2.9 arcsec as the median condition is more pessimistic than to Chun's 2002 SCIDAR median estimate of r_0 = 17.8 cm and θ_0 = 3.17 arcsec (counting all data). At the same time our model is even more pessimistic compared to Neyman's CN-M1 value of r_0 = 20 cm, but slightly optimistic[6] than θ_0 = 2.5 arcsec. Going further back, our choices are also slightly pessimistic with the "MK" model of Sandler, et al. (r_0 = 18 cm, θ_0 = 3.0 arcsec) adopted back in 1991[1] (see also [2]).

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[1] C. Max, private communication. Also comments made at 2007 Keck Strategy Planning meeting did not favor the 62.5% assumption.

[2] (87.5% – 37.5%) / (100% – 25%) = 2/3

[3] This model was first proposed as the" RD Keck Ridge (RDKR) Final" model in an NGAO team internal email on July 6, 2007.

[4] r_0 scales as the 6/5th power of observing wavelength.

[5] The definition of isoplanatic angle includes a number of idealized assumptions, including infinite pupil size and infinitely fine spatial sampling. The effective isoplanatic angle, loosely defined as the angular radius over which Strehl performance drops by an e-fold, is typically 3-4x larger than θ_0.

[6] Our worse r_0, but better θ_0 is consistent with more ground-layer turbulence fraction than assumed by Neyman. This is qualitatively consistent with Flicker's model in KAON 429 (r_0 = 15.6 cm, θ_0 = 3.10 arcsec), which was based on Gemini ground-layer AO studies (Gemini Ground Layer Adaptive Optics Feasibility Study Report (23 February 2005).

3.2 $C_n^2(h)$ distributions

We wish to integrate both the high-altitude turbulence data of the TMT T6 MASS/DIMM, and the overall seeing and isoplanatic angle statistics from the Mauna Kea ridge. To protect the confidentiality of the T6 campaign, still in progress, we proceed according to the following algorithm:

1. Extract the relative weighting of turbulence layer strengths from the T6 MASS/DIMM data set, for different percentile seeing conditions, discarding the ground-layer turbulence contribution.

2. Inject sufficient ground-layer turbulence, while rebalancing the relative weight of the ground-layer and integral of the upper layers, in order to match the r_0 and θ_0 values in Table 1.

Following this process, we arrive at the fractional $C_n^2(h)$ turbulence values in Table 2. It is interesting to note that turbulence is redistributed moving between these models, with the primary effect being the injection of a high altitude seeing layer (4000 and 8000 m altitude layers) in the "challenging" turbulence conditions[7].

Mauna Kea Ridge Turbulence Models				
Altitude (m) above Ground	"Excellent" 87.5%	"Good" 62.5%	**"Median" 50%**	"Challenging" 37.5%
0	0.582	0.482	**0.517**	0.464
500	0.120	0.133	**0.119**	0.109
1000	0.054	0.065	**0.063**	0.060
2000	0.073	0.072	**0.061**	0.062
4000	0.076	0.109	**0.105**	0.135
8000	0.035	0.077	**0.081**	0.113
16000	0.060	0.062	**0.054**	0.057

Table 2. Fractional distribution of $C_n^2(h)$ for the Mauna Kea Ridge Turbulence Models.

4. Wind Model

4.1 Turbulence-weighted wind speeds

In many cases in adaptive optics, an important temporal quantity is the turbulence-weighted wind speed:

$$v_w = \int C_n^{\,2}(h)\, v(h)\, dh$$

which is a proxy for the wind speed of an equivalent thin layer of atmosphere having all the turbulent energy present.

We adopt here a basic vertical wind structure model, based on the classical model by Greenwood[3], but scaled to match the 6.7 m/s mean ground wind speed and 26.8 m/s peak wind speed (at 12km ASL) report by Bely[4].

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[7] This is approximately consistent with Sandler's "MMK" model, which also injected a high altitude turbulence layer, though ours is not as high nor as strong.

Altitude (m) above Ground	Mauna Kea Ridge Wind Speed Profile (m/s)
0	6.8
500	6.9
1000	7.1
2000	7.5
4000	10.0
8000	26.9
16000	18.5

Table 3. Mauna Kea Ridge wind speed profile. We assume these speeds represent the component of wind velocity transverse to the viewing direction.

We shall assume these are ‘average’ v_w conditions, with $v_w = 9.5$ m/s, according to the MKR median turbulence model defined above. This results a corresponding:

Greenwood frequency at zenith = 28.0 Hz.

To explore other wind conditions, we adopt the following bounding model values, simply twice and half the average turbulence-weighted wind speed:

NGAO wind condition	v_w (m/s)	f_G, median turbulence (Hz)
“Fast”	19.0	56.1
“Average”	9.5	28.0
“Slow”	4.75	14.0

Table 4. Mauna Kea Ridge Wind Condition Definitions. The Greenwood frequencies listed here correspond to the median vertical turbulence height profile.

We may sometimes wish to combine the turbulence and wind condition definitions in different ways (e.g. challenging / fast ($f_G = 64.7$ Hz) for near worst-case conditions or excellent / slow ($f_G = 9.9$ Hz) for near best-case), but because Greenwood frequency is a rather slow function of r_0, the values in Table 4 are likely to be convenient approximations for any turbulence profile.

References

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[1] D. G. Sandler, S. Stahl, J. R. P. Angel, M. Lloyd-Hart, and D. W. McCarthy, 1994, “Adaptive optics for diffraction-limited infrared imaging with 8-m telescopes,” JOSA A 11, 92.

[2] Roddier, F., et al., “Seeing at Mauna Kea: a joint UH-UN-NOAO-CFHT study”, Proc SPIE 1236 Part 1, 485-491 (1990).

[3] Greenwood, D. P., 1977, JOSA 67, 3, pp. 390 - 393.

[4] Bely, P., 1984, PASP 99, 560, (1987).