Keck Adaptive Optics Note #303

Atmospheric Parameters for Mauna Kea

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1. Introduction

This memo covers the atmospheric parameters of interest for the design of an adaptive optics system on Mauna Kea. I reviewed the literature for information on seeing statistics at Mauna Kea. In particular, the C_n^2 profile previously used in some AO designs for Mauna Kea was probably incorrect. I propose a new profile based on more recent information. Unless explicitly stated otherwise, values for atmospheric parameters, such at r_0, are given at a wavelength of 0.50 microns.

The initial CN-M1 model has undergone two revisions during the development of the Next Generation Adaptive Optics (NGAO) project at Keck in spring of 2006. These revised modes are denoted CN-M2 and CN-M3. The main changes are an increase in the boundary layer turbulence to make the r_0 18 cm and the inclusion of a finite outer scale of 75 m. All three models are also tabulated on the NGAO twiki site at:
http://www.oir.caltech.edu/twiki_oir/pub/Keck/NGAO/SystemsEngineering/CN-M3atmos.txt

2. Integrated seeing parameters

Historically Mauna Kea has been regarded as one of the best astronomical sites in the world since its inception in the 1970s. Early work on characterizing the site by Bely[1] in 1987 used metrological information and observer logs. The mean surface wind speed was found to be comparable to the wind speed measured in the free atmosphere at the same altitude. The free atmosphere data was gathered by radiosondes (balloons). The mean surface wind speed at CFHT was found to be 6.7 m/s (13 knots). The mean maximum wind speed in the troposphere was 26.8 m/s (52 knots) at an altitude of 12 km above mean sea level (msl). The altitude of Mauna Kea is taken to be 4.2 km (msl). Bely found relatively poor image quality at the telescopes operating at that time. Average image quality was of the order 0.8-1.2 arc sec FWHM. He theorized that this was due to local effects such as mirror, dome, and, telescope seeing. Using metrological models for the C_n^2 profile he estimated that the intrinsic image quality could be as good as 0.3 arc sec FWHM.

A more complete work on the seeing was the study by Racine et al.[2] using the high-resolution camera (HRCam) at the Canada France Hawaii Telescope (CFHT) combined with temperature measurements made in the CHFT dome. The thermal data was used to access the periods when dome or mirror seeing would have had little or no effect on the image quality recorded with the HR camera. These authors find that the median natural seeing at CHFT was 0.43 arc seconds FWHM at a wavelength of 0.7 microns. This value is represents a long exposure FWHM with no tip-tilt correction. The authors applied a suitable broadening correction to the tip-tilt corrected HRCam data. Using the relationship that the Fried parameter r_0 is related to the FWHM by

[1] Bely, P., *PASP* 99, 560, 1987.
[2] Racine, R., Salmon, D., Cowley, D., and Sovka, J., *PASP* 103, 1020, 1991.

$$FWHM = 0.98 \frac{\lambda}{r_0}.$$

These image widths correspond to an r_0 of 0.22 cm at a wavelength of 0.50 μm.

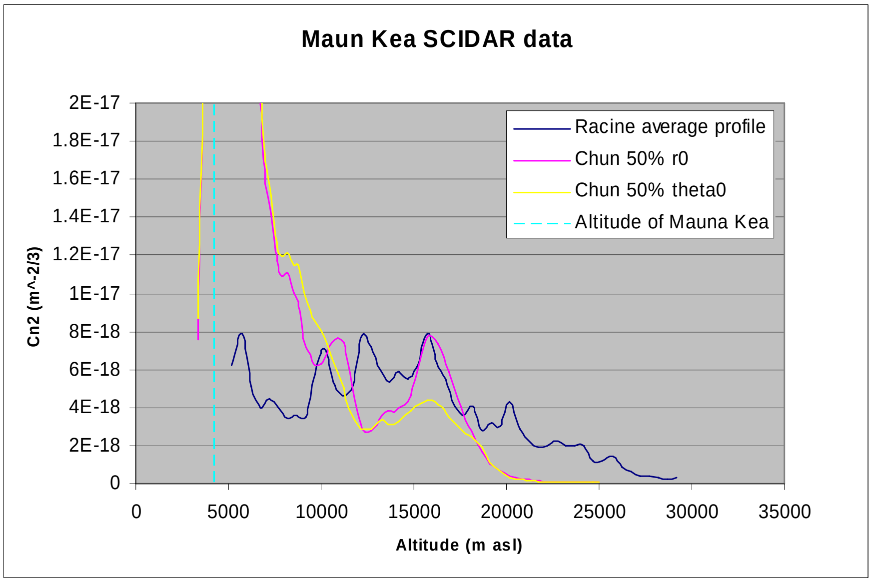

Figure 1. Average C_n^2 Profile from Racine compared to θ_0 50% and r_0 50% profiles from Chun, note this is a linear scale. The scale is adjusted to better show the high-altitude layers, also see Figure 2.

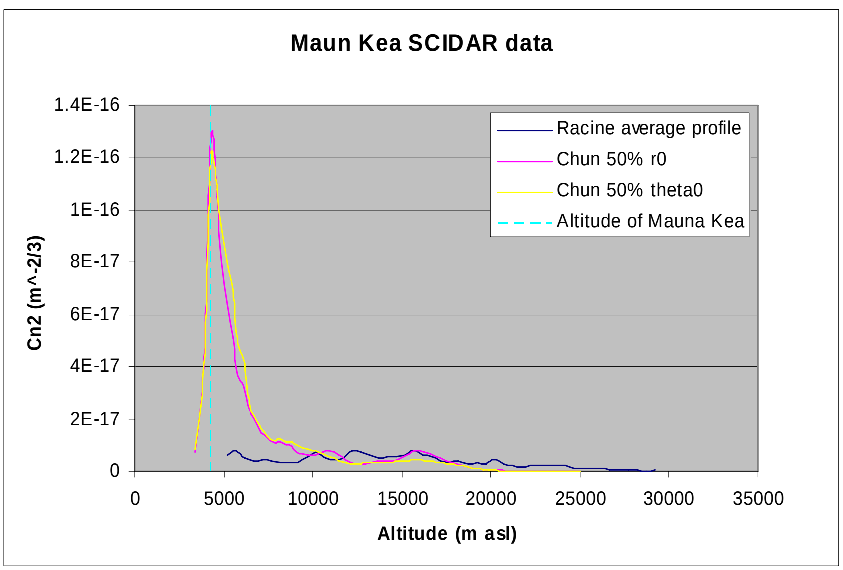

Figure 2. Comparison of Average C_n^2 Profile from Racine compared to θ_0 50% and r_0 50% profiles from Chun, note this is a linear scale. The scale is adjusted to better show the boundary layer, also see Figure 1.

More recently the Subaru telescope has compiled seeing statistics from auto guider images made during checks of the telescope focus. Measurements are made three times during the night, early evening, around midnight and in the early morning. The measurements were complied over the time span May 2000 to June 2001 and summary plots are available on the Web.[3] Taking the peak of the morning seeing plot to represent performance after the dome, mirror and telescope has come into thermal equilibrium with the surrounding atmosphere, and therefore, being typical of the seeing in the atmosphere alone. The early morning value for the seeing is 0.45 arc seconds at 0.7 μm. This corresponds to an r_0 of 21 cm at 0.5 μm wavelength. Subaru also complied a monthly average for the seeing over a 4-year period these values give a more pessimistic value for the natural seeing of 0.63 arc sec which corresponds to r_0 of 15 cm at 0.5 μm.

3. Measurements of the C_n^2 Profile

An important parameter for adaptive optics is the distribution of C_n^2 with height. The first attempt to measure the C_n^2 profile at Mauna Kea was undertaken by Roddier in 1987-1988 using a SCIDAR system at the UH-88 inch telescope. He compiled a total of 414 profiles from a total of 20 nights. These nights were distributed in two observing runs one of 12 nights duration in November 1987 and one of 8 nights duration in June 1989. Since these were basic SCIDAR observation and not generalized SCIDAR observation they are not sensitive to turbulence between 0-2 km above the summit of Mauna Kea. A synopsis of these data was published by Racine[4] in 1994. Racine produced an average C_n^2 profile that represented the background turbulence. Before averaging he removed the sporadic strong layers from the data set. This profile is reproduced in Figure 1and Figure 2 . As noted above the profile has no measurements below about 2 km. The Fried parameter that results from integrating this average C_n^2 is 30 cm at 0.5 μm. The isoplanatic angle is 2.1 arc seconds at 0.5 microns. The r_0 value appears to be high for typical turbulence conditions on Mauna Kea for the reasons mentioned above. If one just scales this profile to the average value of r_0 the resulting profile overestimates the strength of high altitude turbulence. Overestimation of high-altitude turbulence results in a smaller value of the isoplanatic angle and an overestimation of the effective height of the turbulence. Based on Racine's analysis the GEMINI AO system ALTAIR was designed with a DM conjugate to 6.5 km. At this time it appears that gains in isoplanatism predicted by Racine for Mauna Kea are not as large as hoped. Francois Rigaut[5] has indicated that this is due to the turbulence being located at other altitudes or problems caused by the need to run a more complicated control algorithm when the DM is not conjugate to the pupil. He commented that the GEMINI staff is working to detangle these two effects and may in the future move the DM back to a ground conjugate system.

The other researchers have also noted that the turbulence may not be concentrated in high altitude layers. Flicker and Rigaut[6] measured isoplanatism using the University of Hawaii curvature sensor AO system on the GEMINI telescope. Using data from 7 nights that span only a 2-month period they found that the effective height of the turbulence was 3.5 km. They also fit both the r_0 and θ_0 to the images they collected on each night. I will discuss this data in more detail below.

Table 1. Comparison of MASS and SCIDAR results from Tokovinin[7] the integrated parameters were calculated by the author (CN).

	20-Oct		21-Oct		22-Oct		24-Oct	
height	SCIDAR	MASS	SCIDAR	MASS	SCIDAR	MASS	SCIDAR	MASS
500	2.2E-14	1.8E-14	1.5E-14	3.7E-14	2.4E-14	7E-14	3.5E-14	5.3E-14
1000	6E-15	1.4E-14	1.3E-14	1E-14	1.2E-14	4E-15	3.2E-14	1.5E-14
2000	9E-15	6E-15	1.5E-14	8E-15	1E-14	2E-15	2.5E-14	5E-15
4000	3.8E-14	1.4E-14	3.7E-14	1.9E-14	2.9E-14	1.4E-14	1.7E-14	7E-15
8000	6.6E-14	9.4E-14	4.3E-14	5.6E-14	2.7E-14	2.6E-14	4.7E-14	4.3E-14
16000	1.6E-14	1.3E-14	3.2E-14	2.4E-14	1.5E-14	1.2E-14	3E-14	2E-14
total Cn2	1.57E-13	1.59E-13	1.55E-13	1.54E-13	1.17E-13	1.28E-13	1.86E-13	1.43E-13
r0 cm@500nm	24.41204491	24.22734	24.60056	24.69627879	29.12275	27.5942103	22.05140091	25.8191731
theta0 @500nm	2.215415347	2.111619	1.969135	2.12286531	2.852301	3.226134193	2.02223422	2.447193688

In the fall of 2002 a group lead by Mark Chun at the U of Hawaii brought many seeing monitors and atmospheric profilers to Mauna Kea for a 2 month seeing measurement campaign. Unfortunately only a brief comparison of SCIDAR and MASS data from A. Tokovinin was published[7] from this study. The sensitivity of the MASS instrument to ground layer turbulence is not clearly discussed in this report, but it appears that the MASS measures

[3] Subaru seeing measurements at: http://www.naoj.org/Observing/Telescope/Image/seeing.html
[4] Racine, R., Ellerbroek, B., SPIE 2534, (1994).
[5] Riguat, F. private communication (2004).
[6] Flicker, R., Riguat, F. PASP
[7] Tokovinin, A.., http://www.ctio.noao.edu/~atokovin/profiler/index.html., see file, compare.pdf.

the integral of C_n^2, (i.e., units $m^{1/3}$) in five bins located at altitudes of 0.5, 1, 2, 4, 8, 16 km above the summit. The "response functions" of the MASS analysis are such the turbulence is integrated over a triangular function that peaks at the stated layer altitudes and goes to zero at the altitudes of the adjacent layers. For example, the 8-km layer integrates turbulence over a triangle that extends between 4 and 16 kilometers and peaks at 8 km. Tokovinin calls these triangles "slabs" of turbulence. The low-altitude layer centered at 0.5 km must go to zero at 0 and 1 km. The summary results from Tokovinin are given in Table 1 with integrated parameters r_0 and θ_0 calculated by this author. The results for the SCIDAR and the MASS are approximately the same and the integrated values are consistent with each other. Further, these integrated values are also consistent with other values reported at Mauna Kea if we assume that a boundary layer missing in the MASS data is responsible for the larger r_0 reported from the MASS data.

Table 2. The statistics taken from SCIDAR on Mauna Kea in 2002 from Mark Chun.

	20 % best	Median	80% worst
r_0	23.6	17.8	13.6
θ_0	4.83	3.17	2.16
h_eff	1385	1835	3235

Recently I have obtained the averaged SCIDAR profiles from Mark Chun[8]. The profiles are from a one-week run in October and a one-week run in December of 2002. The data were taken from the Generalized-SCIDAR of Jean Vernin mounted on the UH88" telescope. Chun reported that the seeing was somewhat worse than typical Mauna Kea seeing but not exceptionally poor. A total of 20,700 profiles were analyzed. The resulting stats are given in Table 2. Chun also averaged 2000 profiles that were close to the median r_0 and θ_0 from the Table 2. These profiles are plotted in comparison to Racine's average profile in Figure 1and Figure 2. The integrated parameters assume that all turbulence measured below the altitude of Mauna Kea in located at telescope, this will include some contribution from dome seeing resulting in r_0 values that are too small when compared to free atmospheric values.

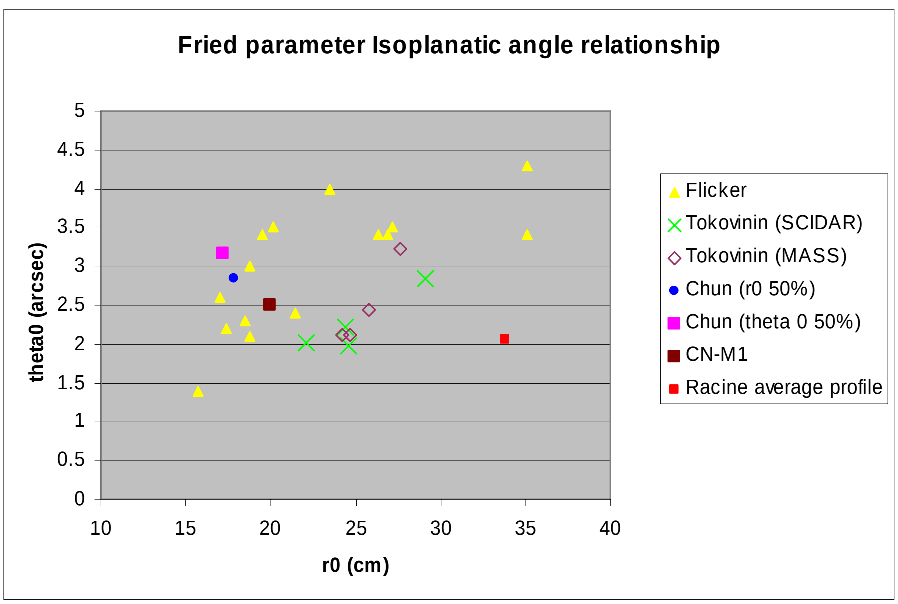

Figure 3. Integrated parameters for r_0 and θ_0 from Flicker, Chun, Racine and Tokovinin.

[8] Chun, M. Unpublished results of atmospheric measurements on Mauna Kea, 2002.

3. Rational for Model CN-M1

In order to compare profiles and integrated parameters I plotted the r_0 and θ_0 values for all data sources that had both parameters or allowed them to be computed in Figure 3. It is obvious from the plot that the Racine average data doesn't include a substantial fraction of the lower altitude turbulence resulting in an abnormally large r_0. The Tokovin MASS and SCIDAR data probably suffer from the same effect, but to a lesser extent. The CN-M1 model arbitrarily sets r_0 to 20 cm and θ_0 to 2.5 arc sec. These values represent “middle of the pack” values and most of the data contained in Figure 3 is for conditions that are better than these values. The CN-M1 profile was derived from the Chun r_0 50% profile because this SCIDAR has given reasonable numbers when compared to balloon based measurement in Chile. The CN-M1 profile is derived in the following way. The Chun profile was integrated into 7 layers that were located around strong peaks in the profile. Next the integrated profile was scaled to produce a θ_0 of 2.25 arc seconds. I then reduced turbulence in the lowest layer to give a r_0 of 20 cm the resulting 7-layer model is given in Table 3.

The wind profile for the CN-M1 model was determined by scaling a Bely's data for wind speed at Mauna Kea. The wind in the upper atmosphere is somewhat higher than Bely's average number. I chose these numbers to be somewhat conservative and predict a higher Greenwood frequency. These wind values produce a Greenwood frequency that is 39 Hz.

Table 3. The CN-M1 model the value of r_0 is 20 cm, θ_0 is 2.2 arcsec and f_G is 39 Hz. All values are given at 0.5 microns wavelength. These values can be scaled as need to simulate other conditions.

Altitude (km)	Fractional C_n^2	Wind Speed (m/s)
0.0	0.369	6.7
2.1	0.219	13.9
4.1	0.127	20.8
6.5	0.101	29.0
9.0	0.046	29.0
12.0	0.111	29.0
14.8	0.027	29.0

4. Revision of the CN-M1 Model to Include Dome Seeing and Finite Outer Scale

During the development of the NGAO proposal to the Keck science steering committee (SSC) in the spring of 2006, the atmospheric models originally developed in this KAON were revised to include an allocation for dome or ground layer seeing. The strength of the ground layer was increase to make the r_0 18cm while maintaining the isoplanatic angle at 2.2 arc seconds. This results in the atmospheric weights for the higher layers being reduced relative to the layer at 0 km. This model was named CN-M2. A final alteration to the mode was to decrease the outer scale from infinity to 75 m. This model was named CN-M3. Both models are given below for completeness.

Table 4. The CN-M2 model the value of r_0 is 18 cm, θ_0 is 2.2 arcsec and f_G is 39 Hz. All values are given at 0.5 microns wavelength. These values can be scaled as need to simulate other conditions.

Altitude (km)	Fractional C_n^2	Wind Speed (m/s)
0.0	0.4707	6.7
2.1	0.1839	13.9
4.1	0.1066	20.8
6.5	0.0845	29.0
9.0	0.0383	29.0
12.0	0.0932	29.0
14.8	0.0228	29.0

Table 5. The CN-M3 model the value of r_0 is 18 cm, θ_0 is 2.2 arc sec and f_G is 39 Hz. The outer scale in each layer is set to 75m from the nominal value of infinity. All values are given at 0.5 microns wavelength. These values can be scaled as need to simulate other conditions.

Altitude (km)	Fractional C_n^2	Wind Speed (m/s)	Outer Scale (m)
0.0	0.4707	6.7	75.0
2.1	0.1839	13.9	75.0
4.1	0.1066	20.8	75.0
6.5	0.0845	29.0	75.0
9.0	0.0383	29.0	75.0
12.0	0.0932	29.0	75.0
14.8	0.0228	29.0	75.0