DRAFT

Mauna Kea Sky Transparency from CFHT SkyProbe Data

Eric Steinbring[1], Jean-Charles Cuillandre[2] and Eugene Magnier[3]

ABSTRACT

Nighttime sky transparency statistics on Mauna Kea are reported based on data from the Canada-France-Hawaii Telescope SkyProbe monitor. We focus on the period beginning with the start of MegaCam wide-field optical imager operations in 2003, and continuing for almost three years. Skies were clear enough to observe on 76% of those nights; attenuations were less than 0.2 magnitudes up to 60% of the time. An empirical model of cloud attenuation and duration is presented allowing us to further characterize the photometric conditions. This is a good fit to the SkyProbe data, from a minimum due solely to air up to maximum of 3 magnitudes of extinction. This indicates that Mauna Kea skies are photometric (without cloud) an average of 56% of the time, with moderate seasonal variation.

1. Introduction

Sky transparency is a fundamental parameter governing the operation of any optical observatory. Best telescope performance comes when skies are photometric - cloud-free - and in general, efficiency at a given site depends directly on the fraction of time that skies are clear enough to observe. As more telescopes employ adaptive optics (AO) facilities employing lasers, even thin cloud can have a significant effect on telescope operations. Attenuation of the beam from cirrus will not only reduce laser return power and affect AO wavefront-sensor performance, but reflected Rayleigh-backscatter light may be of concern to other nearby optical observatories.

[1]Herzberg Institute of Astrophysics, National Research Council Canada, Victoria, BC V9E 2E7, Canada

[2]Canada-France-Hawaii Telescope, P.O. Box 1597, Kamuela, HI 96743

[3]University of Hawaii, Institute for Astronomy, Honolulu, HI 96822

Several sources of sky clarity measurements are available for Mauna Kea. The longest historical records date back to the 1970s, consisting of observers' nightly notes on sky conditions in the logbooks of the University of Hawaii 88-inch, United Kingdom Infrared Telescope (UKIRT), and the Canada-France-Hawaii Telescope (CFHT). Quantitative measurements have been made in "campaign mode" (McCord and Clark 1979; Krisciunas et al. 1987). But only in the last few years has there existed dedicated instruments for measuring sky clarity. Two of these are the Continuous Camera (CONCAM) operated by the *Night Sky Live* network since 2005 (Shamir and Nemiroff 2005) and the Thirty Meter Telescope (TMT) All Sky Camera (ASCA) installed in 2006. Another is the CFHT SkyProbe. The CONCAM and TMT ASCA are all-sky imagers, and as such are best used to provide a panoramic view of cloud cover above the summit. SkyProbe is specifically designed to measure sky transparency as an input to telescope data reduction (Cuillandre et al. 2002).

SkyProbe is fixed to the side of the CFHT. While the dome is open, once every minute it images bright stars in a 35 square-degree field, performs automated photometry, and returns the a measurement of attenuation corrected for zenith angle. It derives an absolute zeropoint based on the Hipparcos' Tycho catalog, which provides a solid photometric reference. An excellent feature of this design is that this measurement is in the direction of the telescope, and as such can be directly compared to a concurrent zeropoint measurement of another instrument, for example the MegaCam imager. Nearby weather measurements from the CFHT meteorological tower can also be used to check for consistency. SkyProbe does not take data at all times though, as it is shut off when the dome is closed.

One utility of SkyProbe, helpful for the observer in pruning data of poor quality, is the detection of clouds. Thick clouds, say 0.5 magnitudes in extinction or more, are easily recognized by sharp fluctuations in attenuation. Less obvious are thin clouds, especially as their attenuation approaches that of the atmosphere itself. To elucidate this, it is useful to separate attenuation into air and cloud components as

$$A = A_{\rm air} + A_{\rm cloud} = A_{\rm air,1} M + A_{\rm cloud,1} T, \tag{1}$$

where cloud thickness T is analogous to airmass M. Like M, it parameterizes the bulk quantity of absorber without making any assumptions about its distribution along the beam. Constants $A_{\rm air,1}$ and $A_{\rm cloud,1}$ indicate attenuations for $M = 1$ and $T = 1$. Separated in this way, it can be seen that if conditions are usually photometric,

$$A_{\rm air,1} = \hat{A}, \tag{2}$$

where $\hat{A}$ indicates the mode of A, and

$$A_{\rm cloud,1} = \bar{A} - \hat{A}. \tag{3}$$

So clouds are detectable if their attenuation is greater than $\hat{A}$ or when T varies on timescales shorter than M - or both.

Under photometric skies, astronomers often fix their photometry to a zeropoint assuming an airmass $M = 1$ at zenith for the observatory, although that is not strictly true. The density of air fluctuates with barometric pressure and temperature, and the concentrations of water vapour and other atmospheric constituents such as carbon dioxide and aerosols (Chambers 2005). To first order, however, airmass will increase linearly with barometric pressure p and relative humdity ρ,

$$M = p\rho/(\bar{p}\bar{\rho}). \tag{4}$$

A complication is that ρ measured on the ground does not necessarily correlate with the bulk of the atmosphere, although the dome will be shut for fog. But barometric pressure is generally constant during a night. So a plausible empirical model - requiring input only from SkyProbe - is that $\hat{A}$, calculated nightly, tracks the observed atmospheric attenuation. And an even simpler model avoids the details of fluctuations in airmass entirely. This assumes that highs in barometric pressure (or any other atmospheric parameter) will be balanced by corresponding lows, giving a Gaussian distribution with a long term average of

$$\bar{M} = \frac{1}{\sqrt{2\pi}\sigma} \int_0^\infty \exp\Big(-\frac{(M-1)^2}{2\sigma^2}\Big)\, \mathrm{d}M = 1, \tag{5}$$

where σ is the standard deviation in nightly $\hat{A}$, expressed as a percent.

When clouds are present, they may go unnoticed if they are thin, persistent and of uniform thickness. One possibile means of detection is motivated by the fractal properties of stratus and cirrus clouds (Ivanova 2000, 2002), in that their density and lifetime are correlated over many orders of magnitude, governed by a tight power law. If so, the number of SkyProbe samples of attenuation $A_{\rm cloud}$ should follow

$$N(A_{\rm cloud}) \propto \exp(-A_{\rm cloud}/\alpha A_{\rm cloud,1}), \tag{6}$$

where α is a constant. This is equivalent to saying that thicker clouds obscure the telescope for less time. Let us assume for now that the duration δ of a cloud is given by

$$\delta = \delta_0 \exp(-T/\alpha), \tag{7}$$

where $\delta_0 = f_{\rm clear}\, t_{\rm obs}$ is the fraction of time that is clear. The average thickness of a cloud is defined to be

$$\bar{T} = \alpha \log(\delta_0/\bar{\delta}) = 1, \tag{8}$$

and since

$$\bar{\delta}/\delta_0 = \frac{1}{T_{\rm max}} \int_0^{T_{\rm max}} \exp\Big(-\frac{T}{\alpha}\Big)\, \mathrm{d}T \approx \exp(-1/\alpha) \tag{9}$$

for maximal thickness $T_{\max} > \alpha$, the thickness of a cloud would be given by

$$T = 1 - \alpha \log(\delta/\bar{\delta}). \tag{10}$$

This suggests that an observer, after subtracting attenuation due to air, and knowing only α and f_{clear}, could estimate the possible variation in attenuation due to cloud during a night.

In Section 2 we present the SkyProbe data and compare them to contemporaneous MegaCam photometric zeropoint measurements. Then, in Section 3 we show that our simple models of M and T are a good match to these data, reproducing both the effects of atmospheric attenuation and up to 3 magnitudes of extinction by clouds. A summary of the results follows in Section 4.

2. Data

SkyProbe V-band data were obtained from the period 1 January 2003 through 31 October 2005. Each record runs from 7 PM to 5 AM Hawaii Standard time, with very few nights lost to the instrument being down. Weather data from the CFHT meteorological tower were obtained for this period. The fraction of time when either SkyProbe did not take data, or the dome shutter was closed (including due to clouds) was 31.2%. It should be noted that the years 2003 through 2005 include some of the worst winter weather on record at CFHT. Even so, the mean attenuation from SkyProbe is 0.160 ± 0.005 magnitudes per airmass, which is comparable, and even slightly better than the value of 0.206 ± 0.023 reported by Krisciunas et al. (1987) based on UKIRT data spanning 1980 to 1986. This result is also in good agreement with observer estimates of the sky-transparency for MegaCam during the period of overlap with the SkyProbe data. Table 1 is a breakdown of the average nights per year lost to each instrument due to weather and telescope downtime, along with the remainder with attenuation less than 0.2 magnitudes.

3. Analysis and Discussion

Median nightly air pressure, temperature, and relative humidity for the CFHT weather tower are shown in Figure 1. Note the strong seasonal variation in air pressure and temperature, with winters clearly evident. There is no obvious seasonal dependence for relative humidity, apart from increased occurances of saturation in winter.

The nightly modal attenuations for SkyProbe are shown below in Figure 1 for the same period. Equation 4 is overplotted as a thick curve. This agrees reasonably well with SkyProbe apart from some deviations, especially during summer months. To help understand these deviations, the median attenuation for each night is overplotted as a thin curve. Both it and equation 4 have been boxcar smoothed to better show trends over a month. When equation 4 and the nightly modal attenuation agree, the median attenuation also tends to agree. Conversely, when the nightly modal attenuation is higher than equation 4, the median attenuation is also high. This could be due to atmospheric attenuation unaccounted for in equation 4, for example, due to Rayleigh scattering and absorption by ozone. This has a minimum of about 0.03 magnitudes at 0.55 μm for the altitude and latitude of Mauna Kea, according to the standard calculation of Hayes and Latham (1975). Seasonal variation in the concentration of aerosols has been seen at other observatories, notably in central Europe (Reimann, Ossenkopf, & Beyersdorfer 1992; Pakstiene 2001). There the variation is thought to be the effect of higher summer temperatures raising smoke and soot into the upper atmosphere, combined with greater absolute humidity. It is not clear that this is the case for Mauna Kea, although it is not inconsistent with the occurances when modal attenuations are "enhanced" over equation 4. Another possible source of attenuation might be thin cloud, and some nights do have modal attenuations of up to 0.45 magnitudes, although that thin cloud persists for months at a time is inconsistent with CFHT observer estimates of sky quality. Further color information for SkyProbe, especially in the red, would be helpful in discriminating between thin cloud and particulates, and a 0.8 μm filter is planned (Cuillandre et al. 2008).

The bottom panel of Figure 1 shows MegaCam zeropoints (subtracted from the minimum zeropoint to indicate attenuation) over the same period, again with equation 4 and the SkyProbe median attenuation overplotted. Note that MegaCam zeropoints are already corrected by the observer for atmospheric attenuation, based partly on comparison with SkyProbe. Deviations from equation 4 seem to coincide with periods when the median SkyProbe attenuation was also high. The value of $\hat{A}$ inferred from MegaCam is 0.074 ± 0.031, taken to be the global mode of attenuations, with uncertainty given by the standard deviation over the same period. This is in agreement with SkyProbe, for which the result is 0.065 ± 0.027.

3.1. Separating Cloud from Air

Figure 2 is a histogram of the SkyProbe data, plotted as attenuation in magnitudes. There is a strong peak at 0.065 magnitudes, indicating the global mode of atmospheric attenuation. To help see this, the distribution of nightly modal attenuations is overplotted as a dashed line. The second "bump" near 0.6 magnitudes is an instrumental artifact. It is caused by untracked exposures at the beginning of the night. At this time the telescope is sometimes parked at zenith and the resulting star trails are not processed properly by the automated software. A total of 145 nights identified with the resulting bogus zeropoint have been isolated and are not included in the analysis, although it is possible that some untracked exposures remain.

Away from the peak associated with the zeropoint, a power-law behavior dominates. A linear least-squares fit to data with 0.4 magnitudes or greater extinction (solid line) gives a power-law slope of -1.84. Comparing this with equation 6 gives $\alpha = -1/(\text{slope} \times A_{1,\text{cloud}}) = -1/(-1.84 \times 0.10) = 5.43$. The fraction of power under this curve (extended to the origin) compared to that in the total distribution is 18.6%. This indicates that for 81.4% of the SkyProbe samples, attenuation was due solely to air. SkyProbe was essentially always operational during the period discussed here and took data whenever the dome shutter was open. Taking this to be 68.8% of the time, conditions were photometric $0.814 \times 0.688 = 56.0\%$ of the time. The true value must be something more than this because downtime due to non-weather reasons (when the sky may not be cloudy) have been included. For example, because SkyProbe is attached to the telescope, datataking is subject to the telescope slewing to a new target.

A more detailed histogram is shown in Figure 3, now plotted only for attenuations less than 0.8 magnitudes; the middle panel is that same, except with the nightly modal attenuation subtracted; and the bottom panel is a cumulative histogram of separated air and cloud. The thick black curve is the result of combining the distribution of nightly modal attenuations (thick dashed curve) with that for the cloud model, indicated by the shaded region. This provides a good fit, although it is possible that the tail of the nightly modal distribution includes some nights when thin cloud was prevalent. To see this, the cloud model combined with the simple Gaussian model of atmospheric attenuation is indicated by the thin black curve. The dotted line indicates Gaussian noise of 0.01 magnitudes about a fixed atmospheric attenuation of 0.065 mag, that is, $\sigma = 0$ and no cloud. This effectively restricts the accuracy of subtraction of the modal attenuation, which is the cause of the scatter in the cloud measurements, and ultimately makes the estimate of the clear fraction uncertain to within perhaps 2%.

To see if any more information can be gleaned from the distribution of SkyProbe attenuations, for example, if the clear fraction of time varies seasonally, this calcuation was repeated after binning the data by calendar month. The results are presented in Figure 4. The solid line is the calculation of cloud-free fraction of time, with the lightly-shaded region indicating cloud; dark shading indicates the dome is closed. Note that CFHT is very efficient in maximimizing the amount of time that the dome is open when skies are clear; this fraction of time varies moderately over the year, with perhaps a peak in late summer approaching 60%. This and the values of other parameters appearing in equations 1 through 6 are given in Table 2.

3.2. Simulated SkyProbe Data

So far, we have only fit a power law to the SkyProbe data (as per equation 6) without need for an explicit assumption about the duration of cloud-free skies (other than to bin the data by month). It is interesting to consider for what values of δ_0 equation 10 is a good fit to the data. A computer simulation was developed to help explore this. Seven artificial SkyProbe datasets, assuming $\delta_0 = 1$, 2, 6, 12, 24, 72 and 168 hours, were generated as follows: An initial cloud duration was selected at random from between zero and δ_0. If a duration of zero was selected, then a period of δ_0 had no attenuation. Otherwise, T was calculated via equation 10. A power-law slope of $\alpha = 5.43$ was used. In one-minute timesteps until the end of this period all datapoints each had this value. Then a new random duration was selected and the process repeated for a number of samples similar to the observations. Poisson noise of 0.01 magnitudes was added to simulate instrumental uncertainty. Data lost due to the dome being shut and to overheads was simulated by masking out 31.2% of nights with the highest median attenuation, just as CFHT closes for cloudy nights. As can be expected, since the mean of T has been defined to be unity, each of these simulations has the same mean attenuation, and correspondingly the same mean duration of clouds, that is $\bar{A}_{\rm cloud} = 0.10$ magnitudes and $\bar{\delta} = 2.14$ hours.

The results are shown in Figure 5 along with the SkyProbe data, displayed as grey-scale images. The nightly modal attenuation has been subtracted from the data to provide an estimate of attenuation due only to cloud. Each pixel represents one SkyProbe sample, with white indicating high attenuation. The same stretch is used throughout. Each row is one night of data, with a full year along a column. Instrumental noise is included, so clear skies appear as a uniform grey; black indicates the dome is shut. Small values of δ_0, less than a 24 hours, seem to reproduce the short, thick clouds seen in the data. Larger values of δ_0 provide longer "clouded out" periods, some lasting several days, also evident in the data. But larger values of δ_0 produce too few short, thick clouds.

It may be that a single value of δ_0 is insufficient to reproduce both long-term periods of cloud and the appropriate variation in attenuation during a night. This can be seen in Figure 6, which is a plot of the standard deviation of attenuation as a function of various time intervals. This has been calculated by dividing up each night's SkyProbe data into blocks of a given interval, and calculating the standard deviation over each. This analysis is restricted to attenuations of 0.5 magnitudes or less, so conditions excluding obvious clouds. Shown are values for 1, 2, 5, 10, 15, 30, and 60 minutes, and then every hour up to 10 hours. Note the strong power-law behaviour, as expected from the cloud model. Thin black curves indicate the results for choices of δ_0 shown in Figure 5 plus that of $\delta_0 = 1$ hour; the thick black curve is the average of these. Although the average of the models does not exactly reproduce the data, it is a reasonably good fit, especially for observational durations longer than an hour. That the average of the models underestimates variation in attenuation on timescales less than an hour suggests that δ_0 might include shorter timescales than this. And so it seems that a refined distribution of δ_0 - possibly spread over all timescales - could produce a better fit. But determining this distribution is beyond the scope of this paper. One path to it may be to investigate similarities with the Fried parameter r_0 associated with optical turbulence, where strong self-similar behaviour is also evident.

Something else that can be seen in Figure 6 is that thin clouds set a threshold for photometric accuracy. Even if atmospheric attenuation is subtracted perfectly, if clouds are not accounted for, observations lasting an hour or more will typically incur a 0.03 magnitude absolute error in photometry. This is comparable to the standard deviation in zeropoint measurements from MegaCam (0.031 mag), for example. And it serves as a reminder to observers to obtain frequent photometric standards; further validation of SkyProbe as an instrument dedicated to calibration of sky transparency.

4. Summary

We have presented an analysis of CFHT SkyProbe data covering almost three calendar years beginning in 2003. The results are in agreement with MegaCam data during the same period. The SkyProbe data show that the V-band attenuation had a modal value of 0.065 magnitudes corresponding to 56% of time with attenuation due to an atmosphere without clouds, and that 59% of the time V-band attenuation was 0.20 magnitudes or less (including both air and thin cloud). These estimates are conservative, as they include small telescope overheads. Some modest seasonal variation, $\sim$ 4%, is seen in the fraction of time that skies are clear, but ultimately the accuracy in that estimate is perhaps $\pm$2%, limited by the photometric uncertainty of SkyProbe. As these results are for open dome shutter time on CFHT, and account for overheads, they can be used as inputs to designing AO with lasers, for example.

A power-law model of cloud attenuation and duration has been presented which is a good fit to the SkyProbe data. It is consistent both with the mean attenuation due to thin clouds, and the appearance of brief thick clouds at times causing the “clouding out” of nights. It is hoped that this simple model will lead to further investigation of the self-similar nature of clouds on Mauna Kea and elsewhere, which could possibly lead to improvements in photometric accuracy at the telescopes.

We thank Derrick Salmon and Konstantinos Vogiatzis for their assistance in obtaining data from the CFHT weather tower, and Chris Pritchet for his MegaCam zeropoints. We would like to thank Glen Herriot and Jean-Pierre Veran for helpful conversations, and the Thirty Meter Telescope Site-Testing Advisory Group for useful comments on an earlier internal report on these results.

REFERENCES

Chambers, K.C. 2005, ASP Conf. Ser., 338, 134

Cuillandre, J.-C., Magnier, E.A., Isani, S., Sabin, D., Knight, W., Kras, S., & Lai, K. 2002, Proc. SPIE, 4844, 501

Cuillandre, J.-C. Magnier, E., Sabin, D. & Mahoney, B., 2008, Proc. SPIE, 7016, 25

Hayes, D.S., & Latham, D.W. 1975, ApJ, 197, 593

Ivanova, K., Ausloos, M., Clothiaux, E.E., Shirer, H.N, & Ackerman, T.P., 2000, Tenth ARM Science Team Mtng. Proc., San Antonio, NM, 1

Ivanova, K., Shirer, H.N., Clothiaux, E.E., Kitova, N., Mikhalev, M.A., Ackerman, T.P., & Ausloos, M., 2002, Phys. A., 308, 518

Krisciunas, K., Sinton, W., Tholen, D., Tokunaga, A., Golisch, W., Griep, G., Kaminski, C., Impey, C. & Christian, C. 1987, PASP, 99, 887

McCord, T.B. & Clark, R.N. 1979, PASP, 91, 571

Pakstiene, E. 2001, Baltic Astronomy, 10, 651

Reimann, H.-G., Ossenkopf, V., & Beyersdorfer, S. 1992, Astron. and Astrophys., 265, 360

Shamir, L. & Nemiroff R.J. 2005, PASP, 117, 972

Table 1. Breakdown of SkyProbe and MegaCam Observing Statistics in Nights per Year[1]

	Unobserved				Attenuation (mag)	
Instrument	Dome shut	Overheads[2]	Total	Observed	≥ 0.2	< 0.2
SkyProbe	87 (23.8)	27 (7.4)	114 (31.2)	251 (68.8)	35 (9.6)	216 (59.2)
MegaCam	87 (23.8)	37 (10.2)	124 (34.0)	241 (66.0)	20 (5.5)	221 (60.5)

[1]Averages for a total sample of 1035 nights with SkyProbe and 541 nights with MegaCam. Fractional nights have been rounded down. Percent of total nights in the respective samples are shown in brackets.

[2]Includes time lost during telescope slews, detector readout, technical faults, and engineering downtime.

Table 2. Atmospheric Parameters Derived from SkyProbe[1]

$A_{\mathrm{air},1}$ (mag)	σ	$A_{\mathrm{cloud},1}$ (mag)	α	f_{clear} (percent)
0.065 ± 0.002	0.027 ± 0.002	0.095 ± 0.003	5.43 ± 0.13	56.0 ± 3.6

[1]Averages after binning by calendar month. Quoted uncertainties are the standard deviations in each parameter.

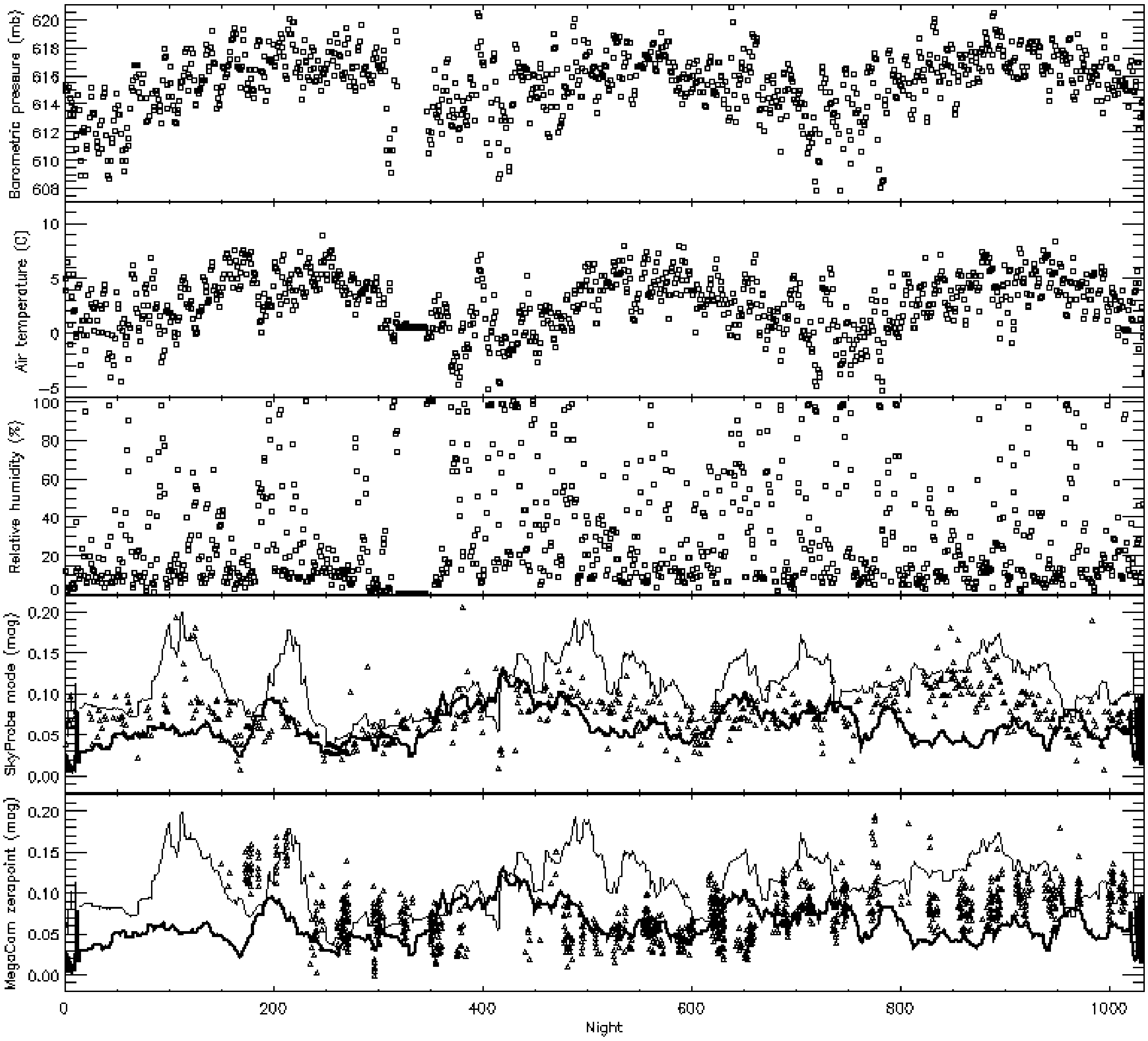

Fig. 1.— Plots of nightly median barometric pressure, temperature, and relative humdity from the CFHT weather tower. Below are nightly modal V-band attenuation from SkyProbe and g-band zeropoint from MegaCam for the same nights. Atmospheric attenuation is overplotted for SkyProbe and MegaCam assuming equation 4 (thick curve), along with the nightly median attenuation (thin curve); each boxcar smoothed to better show variation over a month.

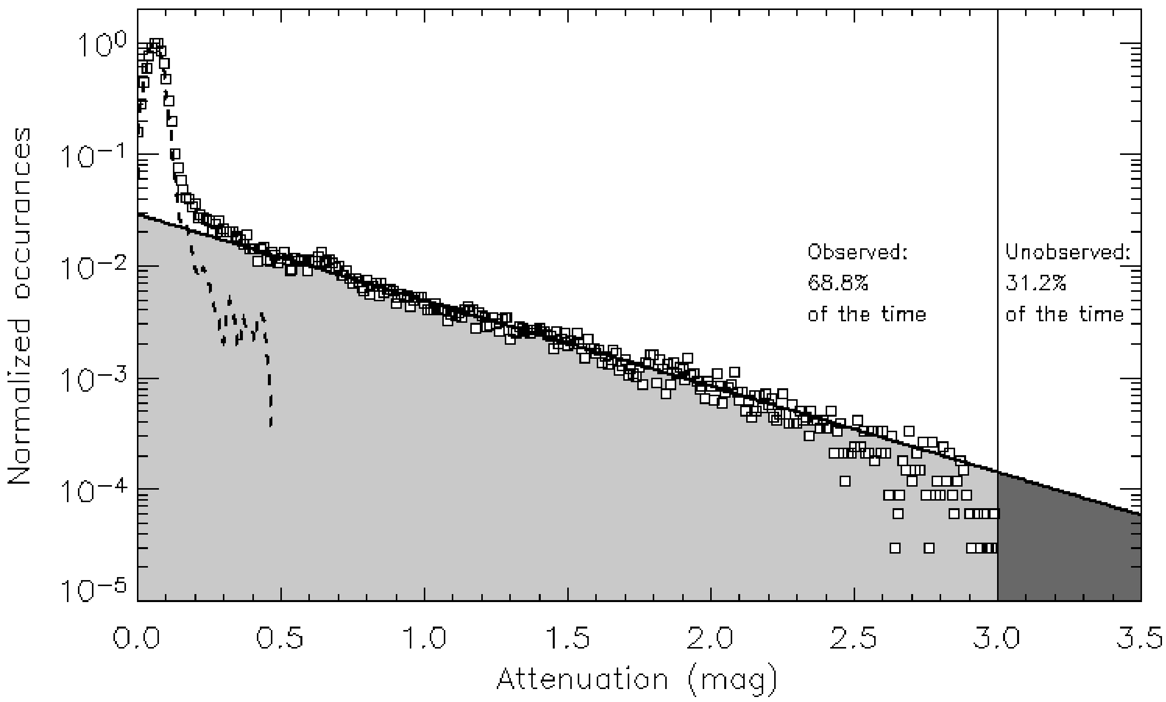

Fig. 2.— A histogram of the SkyProbe data. The peak at 0.065 magnitudes corresponds to the global mode of atmospheric extinction. To help show this, the distribution of nightly modal attenuations is overplotted as a dashed curve. A linear least-squares fit to the data with 0.40 magnitudes or more gives a power-law slope of -1.84 (thick black line) corresponding to a value of $\alpha = 5.43$. See text for details.

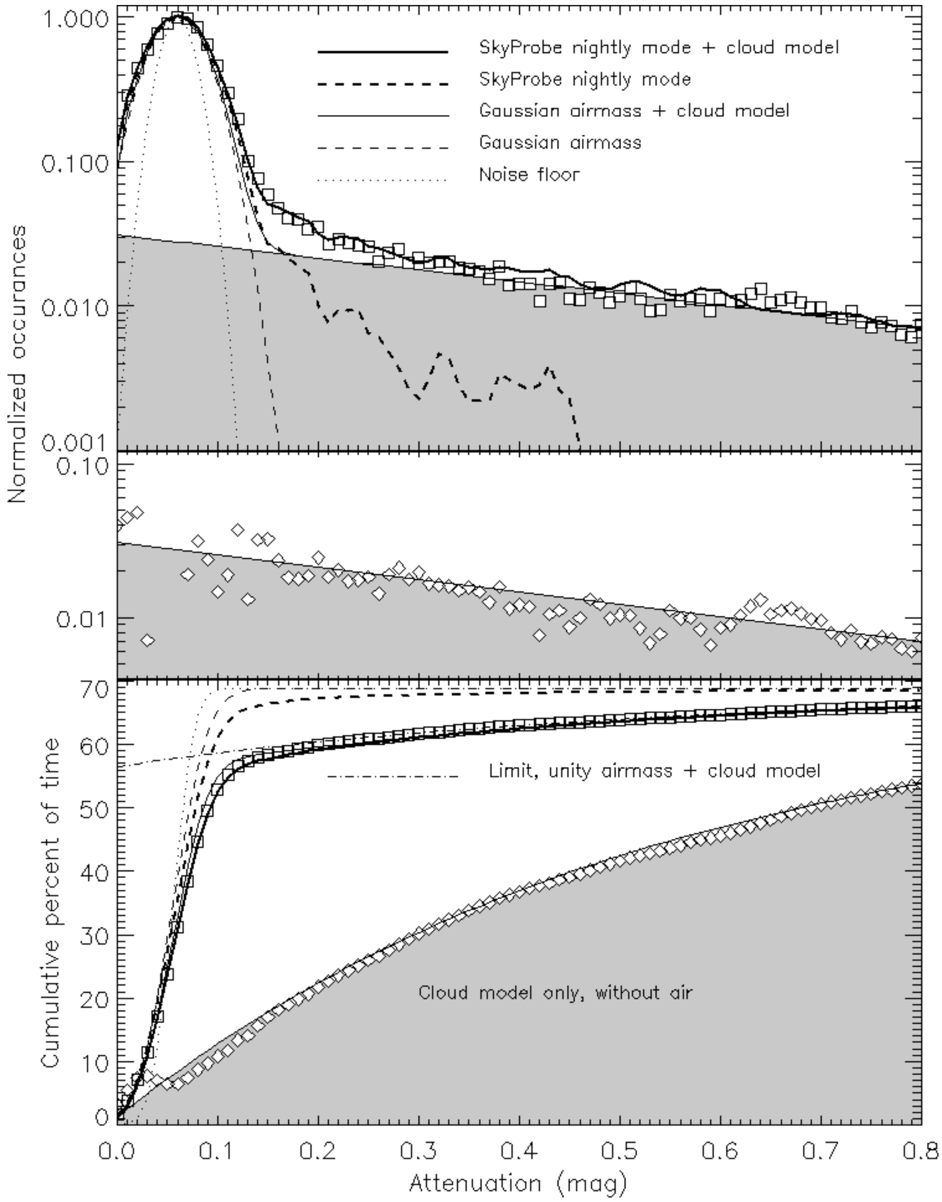

Fig. 3.— A histogram of the data (top panel; squares) that with nightly modal attenuation subtracted (middle panel; diamonds) and cumulative histogram (bottom panel) with a power-law model for clouds indicated by the shaded region. The two models for atmospheric attenuation are plotted as dashed curves, and the combination of these with the cloud model as solid curves. The dotted line indicates the minimum distribution of attenuations for $M = 1$ and photometric scatter of 0.01 mag. The fraction of time during the night without cloud is 56.0%. This is evidently not strongly dependent on the model of atmospheric attenuation used, as both provide good fits to the data.

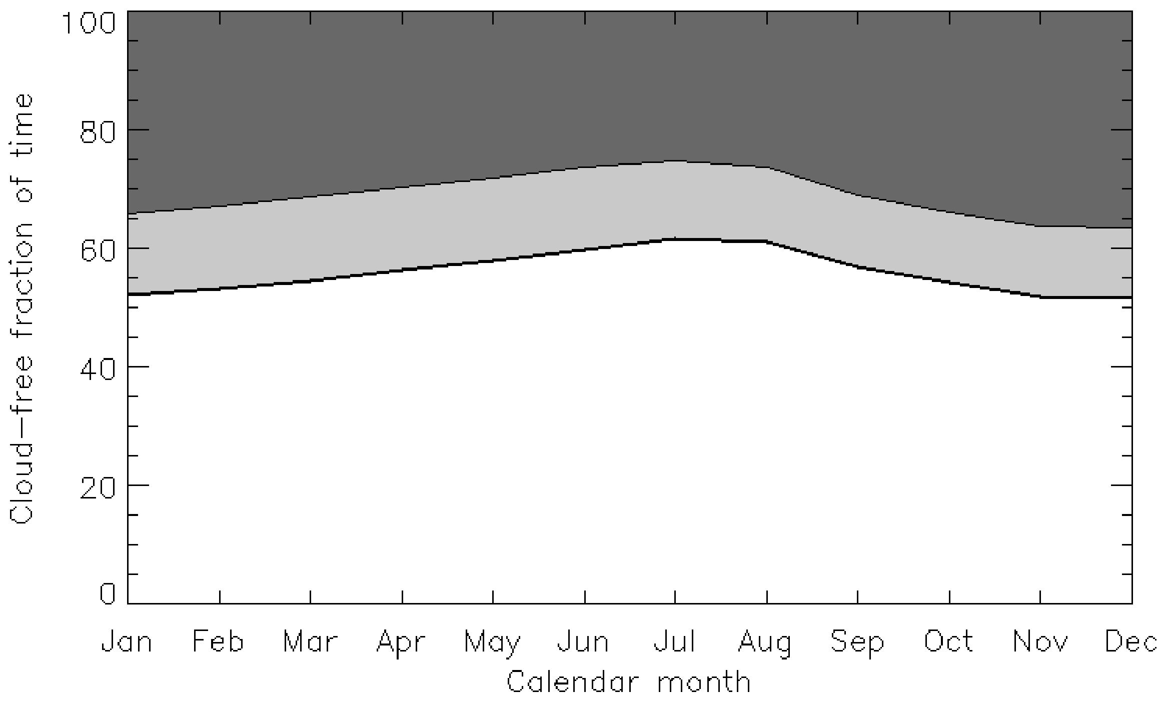

Fig. 4.— A plot of cloud-free fraction of skies for the SkyProbe data calculated for each calendar month. This is corrected for the unobserved fraction of time during the night, indicated by the darkly shaded region. All unobserved samples are assumed to be cloudy (lightly shaded region).

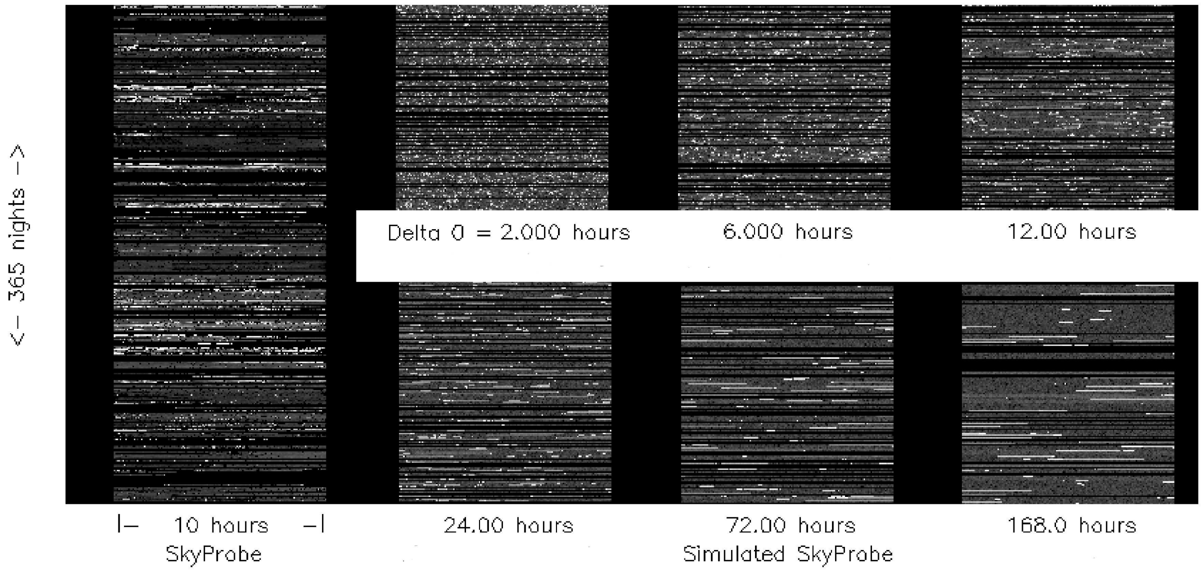

Fig. 5.— Images of the SkyProbe data and simulations. Each pixel represents one SkyProbe sample; white indicating high attenuation with the same stretch used throughout. Noise is included, so clear periods appear grey; times when the dome is closed are black. One night comprises a row. A year of data is shown. Simulations are shown for δ_0 of 2, 6, 12, 24, 72, and 168 hours. None reproduces both the many short thick clouds seen in the data as well as longer “clouded-out” periods of several days.

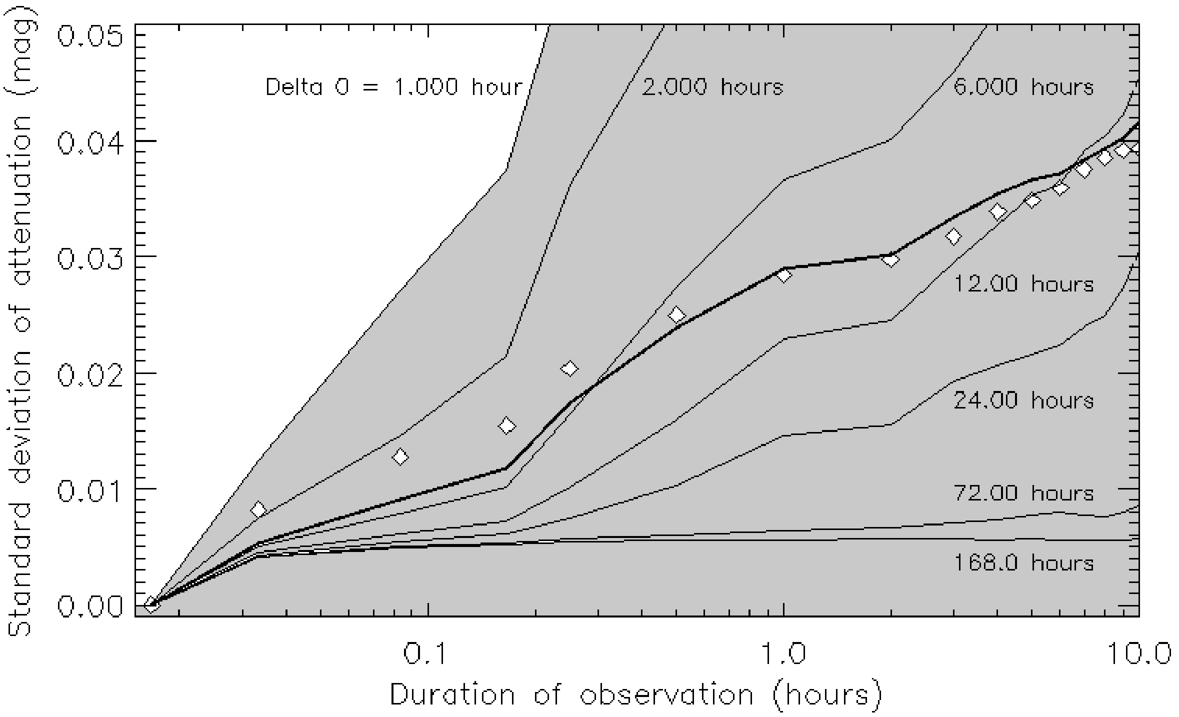

Fig. 6.— A plot of standard deviations in SkyProbe attenuation due to cloud for observations lasting various time intervals, from 1 minute up to 10 hours. The nightly mode of attenuation has been subtracted for each night. The results of the simulations are shown as thin black lines, for δ_0 of 1, 2, 6, 12, 24, 72 and 168 hours; the average of those is indicated by a thick black curve. It would seem a model incorporating an appropriate distribution of δ_0 could reproduce the variation seen in the data.