Seeing Effects Due to SOAR Building Height

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7 January 1999

1 Background

1.1 Site Survey for Gemini

During the years 1988-92 CTIO carried out a site survey in preparation for the Gemini Telescope Project. The SOAR partners of that time contributed some of the funding. This work was supervised by Nick Suntzeff, and is briefly described in the report *Site Considerations for the SOAR Telescope* by Suntzeff and Baldwin (CTIO, July 1997). Most measurements were made from a peak which has since been cut down some 15m to create the platform for the Gemini telescope; the bases of the various instruments were located at about the present position of the Gemini observing floor.

These studies included anemometers, echosonde acoustic monitors, microthermal towers, and small telescopes used for measuring image motion. Results from this survey were used to determine the site for SOAR, and have appeared in various SOAR documents (the *Science Working Group* report, for example).

In summary, high quality seeing data using the image motion monitors were obtained only over the final few months of the survey, but indicated 0.5 arcsec median seeing at the Gemini site. The microthermal measurements showed the low-level turbulence to be quite small, with an integrated FWHM seeing contribution of about 0.06 arcsec from the height range 7-30 m. The echosonde results were problematical, but taken together with the microthermal measurements suggested a total (integrated) FWHM seeing contribution of about 0.11 arcsec from the height range 7-200 m.

1.2 Anemometer Studies at the SOAR Site

In early 1997 there was debate about whether SOAR should be built on Cerro Tololo or Cerro Pachon. The best site on Cerro Pachon appeared to be the one on which we are now building, but there was no detailed information about it. I proposed carrying out a quick measurement of the airflow over the site.

This was intended to duplicate a test which had been carried out by the Gemini project team (at the Gemini site) in order to check the height of the boundary layer, and consisted of mounting 5 sets of 3 anemometers each at 5 different heights on a 30m tower. Each group of 3 anemometers measured the x,y,z wind velocity components at their height on the tower. The uppermost anemometer set (30m height) was assumed to be in the free-flowing air above the boundary layer, and the test consisted of studying the degree of correlation of the wind vector velocity at this fiducial height with the velocities at the other heights. The Gemini results showed the velocities to be well correlated down to about 10m, but that the correlation completely broke down at heights below 10m. The conclusion was that the boundary layer was at approximately 10m.

The attraction of repeating this test at the SOAR site was that it could be carried out for just a short time, to get a sample of the airflow over the site with the wind coming from several directions. Then the results could be weighted by the fraction of time that the wind comes from each direction (taken from the wind rose measured during the Gemini site survey) to give a quick check as to whether or not there were any major turbulence problems associated with the detailed topography.

We proceeded to borrow the anemometers from Gemini, and had them shipped down to Chile. When they got here, some cables were found to be missing, and had to be ordered from the US. Once we had the equipment, we set it up on Cerro Tololo to calibrate it, but several of the anemometers were promptly destroyed by a winter storm. When we finally had everything back together, it had already been decided to go ahead and level the present SOAR site, so we elected to wait and not make any tests until after the site was leveled.

The anemometers finally got going on 19 March 1998. The measurements were continued through 9 October 1998, except for occasional losses of a few days during bad weather (anemometers blown away, frozen solid, etc). The setup has now been dismantled. The instantaneous wind velocities from the 5 sets of anemometers were read out essentially simultaneously at 1-min intervals. A total of 229,000 measurements were made, of which 98,000 were at night.

The basic idea behind this test was that it would measure whether or not the airflow is laminar at each height. Having air bubbles with different refractive index mixed into the light path and acting as lenses to deflect parts of the wavefront produces bad seeing. This requires the combination of turbulent airflow and temperature differences; neither of these two conditions by itself is enough to produce bad seeing. The (perhaps naïve) model is that if the airflow is smooth, we should not have to worry.

Dr. Andre Erasmus called the usefulness of this test into question in an e-mail to Tom Sebring from S. Africa in October. The relevant part of that message reads:

> The use of the anemometers to get the top of the ‘boundary layer height’ is suspect. All the measurements show is that the mean wind increases with height and by how much. It does not define to top of the boundary layer. Turbulence is certainly occurring above 10m -- its just that since the turbulent eddies are isotropic (Kolmogorov revisited) the mean wind speed stays constant above a certain level. The layer below 10m is the turbulence generation region due to the wind shear but turbulence is not confined to this layer only. The anemometer method also leaves out the question of temperature transfer. On MK we found that under moderate to strong winds, CT^2 values do not drop off with height and quite often even increased with height between 6m and 30m. So the behavior of the CT^2 - height profile is especially important under light winds -- this is when you get the most benefit to seeing by going higher. In addition, one can not disregard the thermal component so CT^2 itself must be measured.

I talked about this with the members of the SCIDAR group from the University of Nice when they came to CTIO in November, and they basically agreed with Erasmus that temperature data are needed as well. However, I then also discussed the issue with Dave DeYoung (from NOAO), who had done some important computer simulations of airflow over Cerro Pachon for Gemini. Dave felt pretty strongly that the original idea behind the anemometer tests is correct, and that the tests in fact are meaningful. So there was a range of opinion.

1.3 Microthermal Measurements at the SOAR Site

The questions about the anemometer method arose at a time when a complementary set of tests was already scheduled. Gemini funded a French team led by Dr. Jean Vernin from the University of Nice to come to CTIO and conduct further studies of the site conditions, in order to determine a number of parameters needed for the design of an adaptive optics system for Gemini South. This work included SCIDAR scintillation measurements using the CTIO 1.5m telescope, and microthermal measurements from balloons launched from Cerro Pachon over a period of many months. Mark Chun, of the Gemini staff, is preparing a report on this study. Some of the results used below were taken from a preliminary draft of Chun’s report.

During the SCIDAR team’s final visit in November they also made a series of measurements from the SOAR site on Cerro Pachon. These included image motion measurements made with an array of small telescopes (which measured both seeing and the outer scale length of the air turbulence), and microthermal measurements made using probes mounted on the same tower as our anemometers. The latter test allows a direct comparison between the anemometer and microthermal methods, with the hope that we can calibrate the anemometer results. Preliminary results from the microthermal measurements became available three weeks ago, and are discussed below in section 4.

2.0 Prevailing Wind Direction

A surprise that came from the anemometer data is that the prevailing wind is not from the direction that we expected when the SOAR site was selected. Wind measurements made during the CTIO survey of the Gemini site (hereafter the "Old Gemini" data) showed that the prevailing wind came from NNE, with a very strong peak in the wind rose in that direction. This was accepted without question because the same wind behavior is seen on Cerro Tololo. The SOAR site was chosen because it is on the end of the Cerro Pachon ridge, and protrudes into a north wind like the prow of a ship… presumed to be a good situation for smooth airflow. However, the new measurements made at the SOAR site showed the wind to come primarily from the NW, a difference of over 45°.

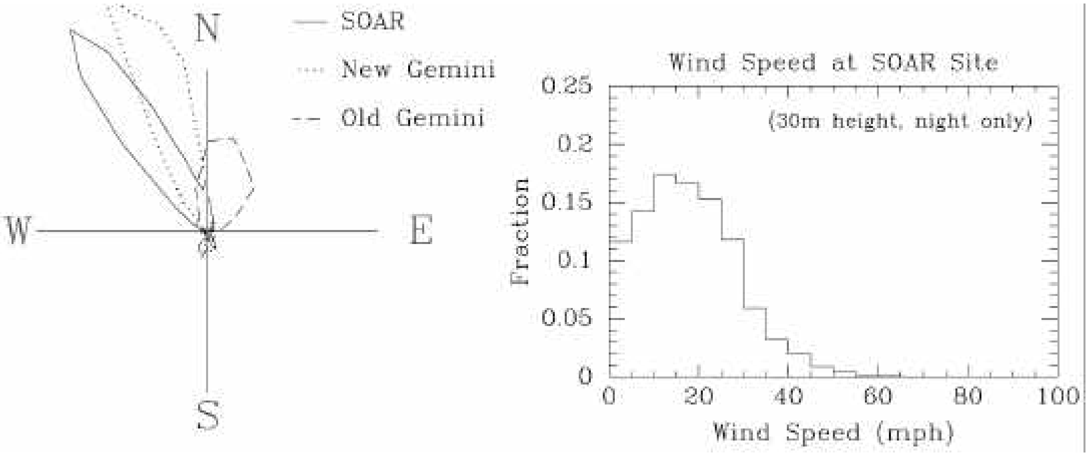


Fig. 1

Figure 1 (left panel) shows these different results, using just the measurements made at night. The Old Gemini wind rose is shown as the dashed line, while the results from the SOAR site are shown as the solid line. Additional wind information is available from a new Gemini weather tower which is located just below the Gemini parking area, part way down the road to the SOAR site. This "New Gemini" data set starts in May 1998 and continues through the present, overlapping in time with the data from the SOAR site. It is shown on Figure 1 as a dotted line.

The difference in the directions of the wind roses for the SOAR data and the New Gemini data may not be real, but rather could be due to the uncertainty in the alignment of the anemometers on the towers. However, the difference between these two data sets and the Old Gemini wind rose is far larger than any alignment errors. I don't know what the cause is. The people who took and reduced the Old Gemini data do not see how they could have made a 90° error or some such thing. We carefully rechecked the directions given in the SOAR data set and I am sure that they are accurate to within 5-10°. However, it is also hard to believe that the prevailing wind direction changed so drastically, in spite of the availability of El Niño as a potential scapegoat. The Old Gemini data were taken from a site which no longer exists, but which is somewhere near the top of the Gemini dome. Given the construction activity on the Gemini building, I have not tried to obtain any new wind measurements in that area. This is an unresolved problem, but none-the-less it is quite clear that the SOAR data set accurately shows the wind rose at the SOAR site during the 8-month measurement period.

The SOAR and New Gemini data were also reduced weighting the wind directions by the wind speed, but the resulting wind roses are almost unchanged from those shown in Figure 1. A histogram of wind velocities for the SOAR site is shown in Figure 1 (right panel). The SOAR wind data shown in Fig 1 are from the anemometers at 30m (the highest point on the tower).

3.0 Airflow Results

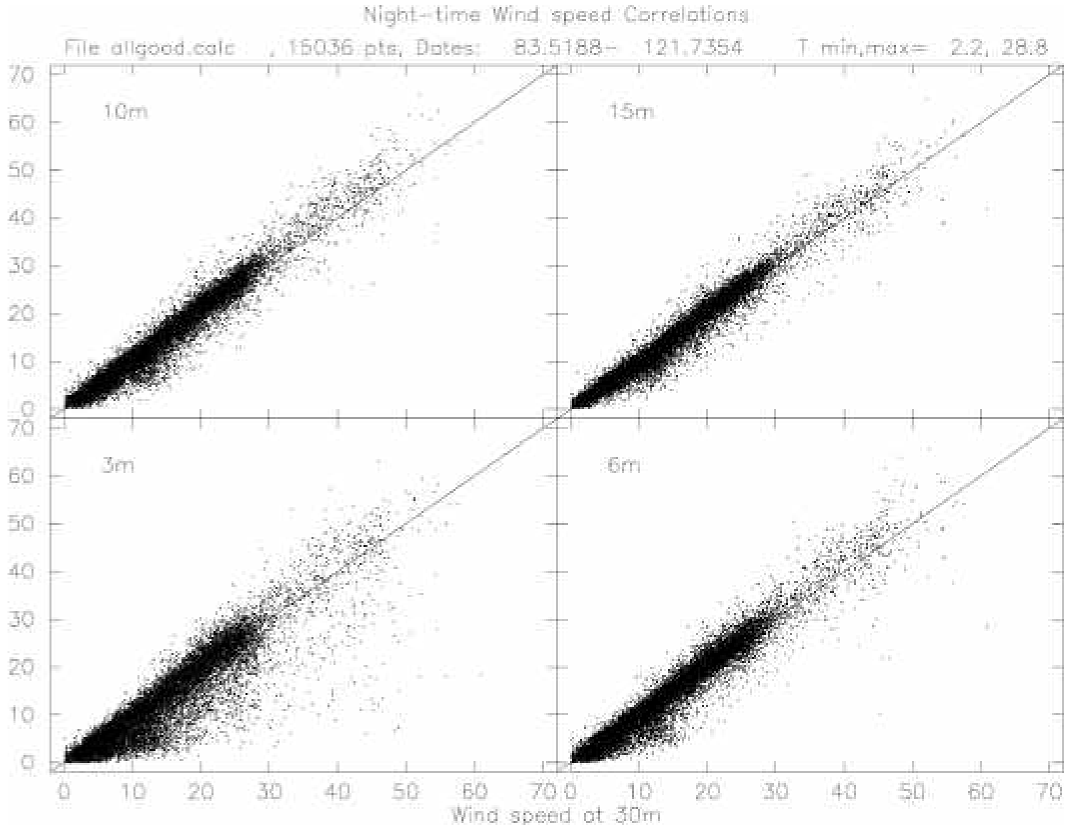


Fig. 2

Typical results from the SOAR anemometer measurements are shown in Figures 2 and 3. In this case data from the 10-day period 24 March – 3 April is shown, but data from almost any other time period look very much like this. Each panel in Fig 2 shows the correlation between wind speed at one of the lower heights on the tower (3, 6, 10 or 15m, plotted along the y-axis) vs. the wind speed at the highest point on the tower (30m, plotted along the x-axis). The diagonal line is for a 1:1 relationship, and it is seen that the points for the 6m, 10m and 15m wind speeds all correlate very nicely with the 30m wind speeds. At 6m the correlation breaks down, particularly at velocities below 10 mph. This is taken to mean that the airflow is very well ordered, and therefore non-turbulent, at heights above about 6m. The smooth airflow extended to lower heights than at the Gemini site.

Figure 3 shows a similar plot from the same data set, this time for the wind azimuth directions (defined as 0° = wind from North, 90° = wind from East). Again, for wind directions between 0 and –90° most of the points fall along a fairly well defined line. The points show a wide scatter when the wind comes from roughly –180° (South), but this corresponds to the wind blowing roughly from behind the Gemini dome and is a direction associated at Cerro Tololo with passing weather fronts (and bad observing conditions).

The noticeably consistent tendency in Figure 3 is that when the wind at 30m (x-axis of plots) comes from about 0°, the wind direction at progressively lower heights on the tower steadily skews around to negative azimuth angles (i.e. towards the west). This means that while the airflow is pretty much plane parallel at all heights on the tower when the wind at 30m comes from NW through W (-45 through –90°), there is a systematic circulation pattern when the wind comes from the North (0°). At the SOAR Board meeting in Chapel Hill in November, I expressed uncertainty about what the building height should be because I did not understand the implications of this circulation pattern.

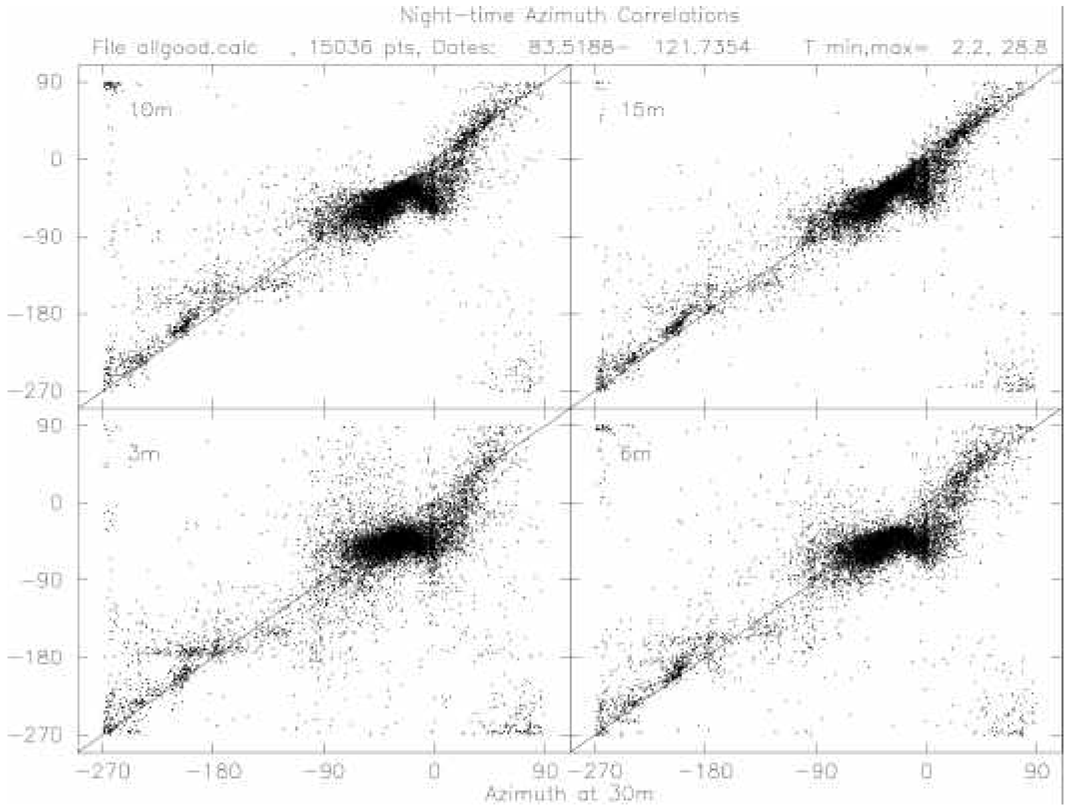


Fig. 3

Releasing colored smoke at the up-wind edge of the site, and studying its flow made an additional measurement of airflow over the SOAR site. The smoke was released first from the ground at the extreme west edge of the site (next to the cliff face), and then from a boom which extended about 2 meters out horizontally to the west over the edge of the cliff. The flow was recorded on videotape, and the flow patterns and areas of turbulence are quite obvious when viewing the tape. I showed a still frame from this tape at the SOAR Concept Design Review last June, but it did not convey anything because it is necessary to see the motion of the smoke in order to visualize the airflow. Figure 4 is a sketch of the airflow patterns that are evident when watching the videotape. The streamlines rise from west to east, separating as they pass over the site. There is an area of turbulence below the streamline coming from the very edge of the summit platform. The height at which we detected turbulence with the anemometers is a function of how far back the tower was placed from the cliff face. The smoke tests were made with the wind blowing from the usual NW direction (-40°) at a speed of 28 mph. Presumably the angle at which the streamlines come up will change according to the wind velocity. Obviously, the further the telescope can be placed to the left on Figure 4, the more it will be above the layers of ground turbulence for a given building height but variable wind velocity. I believe that the building should be placed as far to the west (left in the sketch) as can be done without driving up the building costs.

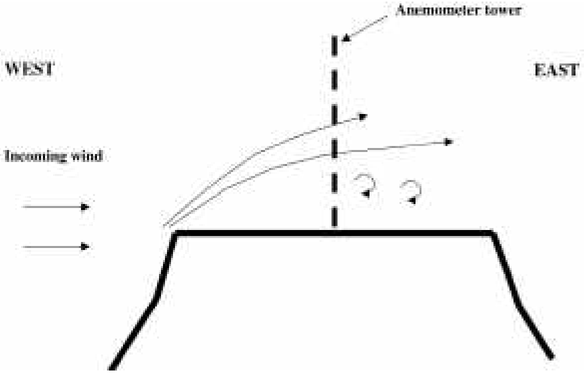
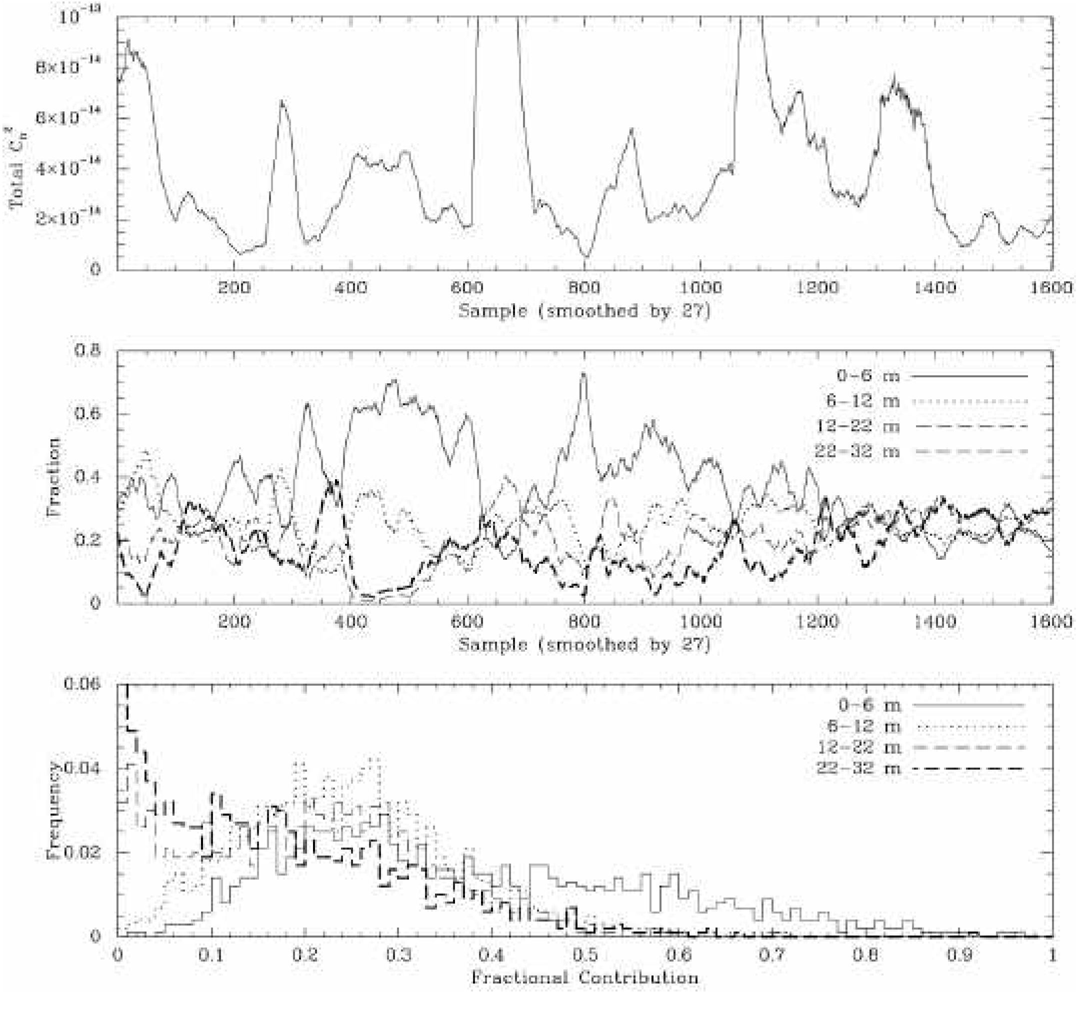


Fig. 4

4.0 Microthermal Results

The Gemini SCIDAR team obtained microthermal data at the SOAR site on 2 partial nights and 2 full nights, during 6-9 Nov. The microthermal probes were mounted on the same tower as the anemometers, but at heights of 4, 8, 16.5 and 27m. The heights had to be different from those of the anemometers in order to avoid having wake effects between the two sets of instruments.

The microthermal data were reduced by Mark Chun and co-workers to give C_n^2, the density structure function used in seeing models.[1] The Kolmogorov seeing theory can be used to convert C_n^2 to r_0 and FWHM: $r_0 \propto (C_n^2)^{-3/5}$, and FWHM $\propto (C_n^2)^{3/5}$. The C_n^2 contribution was integrated over the height of the tower by assuming that the probes at 4, 8, 16.5 and 27m were sampling bins which extended between the midpoints between the probe heights (i.e. the bins covered 0-6, 6-12, 12-22 and 22-32m). Figure 5 follows a plot made by Chun, and shows the fractional contribution from each of these four height bins to the total C_n^2 from 0-32m. The upper panel shows as a function of time the total 0-32m C_n^2 , with small values representing good seeing. The middle panel shows the fraction of the total C_n^2 that comes from each height bin, again as a function of time. Only nighttime data are used, defined at this time of year as being between 0^h and 9^h UT. The time coordinate in these two panels is given as sample number, with 1-minute separation between samples, but big gaps between successive nights and occasional smaller gaps also in the data stream. The data in these two panels have been boxcar smoothed over 27 points in order to make the plots



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[1] A good reference to the Kolmogorov seeing model is the Keck publication "Adaptive Optics for Keck Observatory" (Revised January 1996)… hereafter the "Keck Bible" . Your SAC representative may have a copy.

legible (or at least less illegible).

The lower panel in Figure 5 shows histograms of the frequency with which each of the 4 height bins contributes a given fraction of the total C_n^2. I apologize for the difficulty of reading this plot, but the important point that it conveys is that the lowest height bin (0-6m) is the major contributor to bad seeing. The 6-12m bin, which includes the height presently contemplated for the SOAR telescope and dome opening, does not contribute much more to bad seeing than do the bins representing greater heights. The seeing will gradually get better as you move the telescope to heights above 10m, but from these data the only "magic" height range to avoid appears to be 0-6m.

5.0 Comparisons

The SOAR anemometers were running throughout the microthermal measurements and showed that the wind speed and direction went through most of their usual paces. During the first two nights the wind came from azimuth ~ 0° (the North) at moderate velocities. During the day after the second night there was a weather disturbance during which the wind dropped to almost zero and swung around to come from the south just at the start of the third night. For the last part of the third night and throughout the fourth night, the wind came from approximately its median direction (-30 to –40°, or NW). The wind speed was again moderate (10-15 mph) during the third night and the first half of the fourth night, but then increased to about 25 mph. Figures 6 and 7 show the wind speed and direction correlation plots during this period, in the same format as Figures 2 and 3. The two sets of figures show the same effects. The C_n^2 measurements were therefore taken under a typical range of wind conditions.

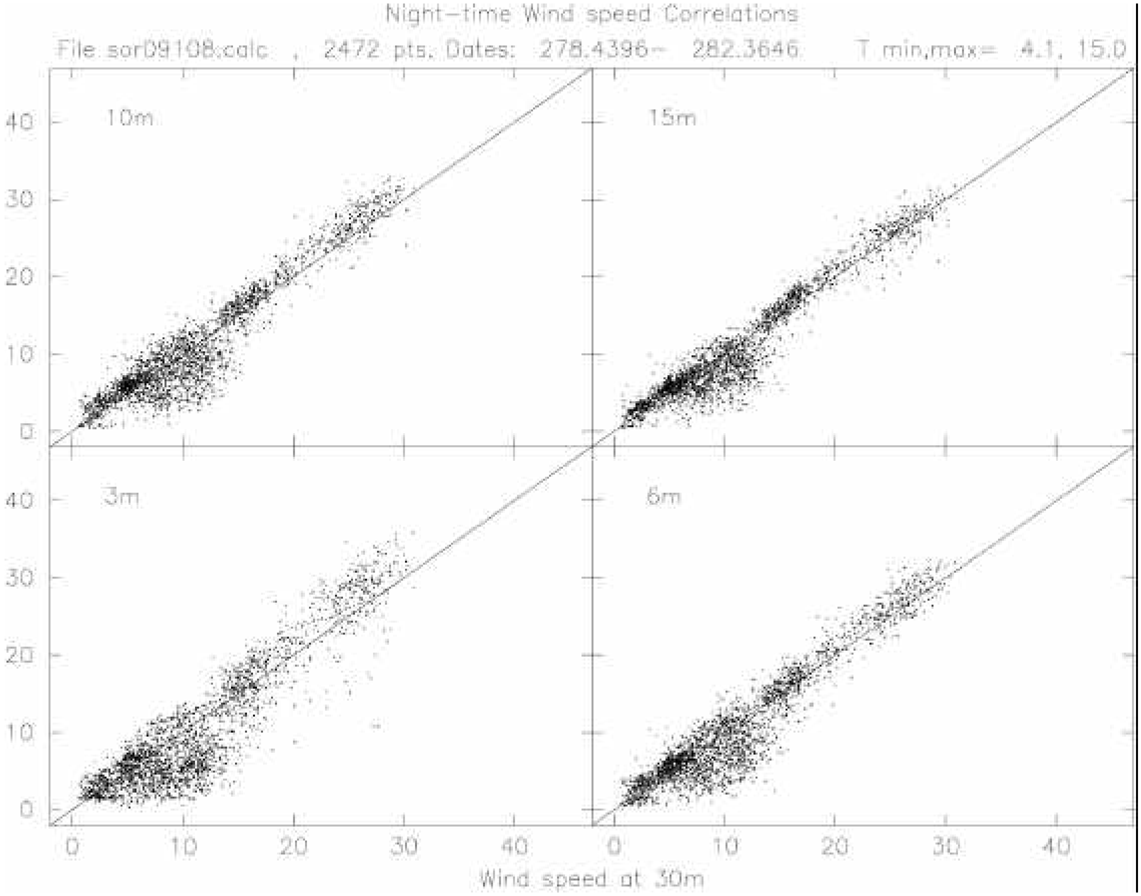

Fig. 6

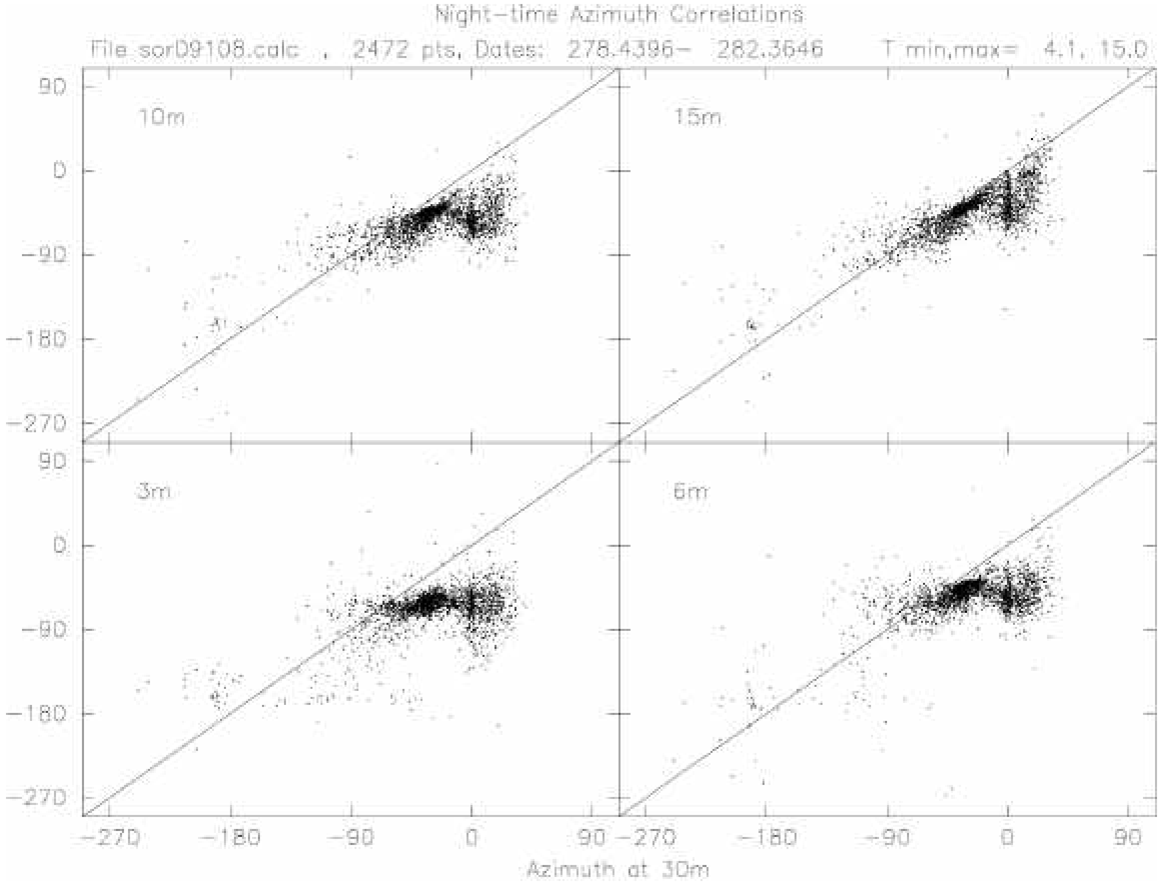

Fig. 7

Both the microthermal and anemometer measurements showed that the effect of levels higher than 6m becomes much more significant during the day. It is important to use only the data taken at night.

I have looked carefully but have not found any obvious relationship between the microthermal results, and the correlation or lack of correlation between wind velocities at different heights. The reservations expressed by Erasmus, and Vernin would seem to be correct, and the anemometer results by themselves do not appear to tell us much. However, as noted above the microthermal results do lead to the same conclusion that I (probably erroneously) drew from the anemometer data that the major effects from seeing near the ground come from below 10m.

It is helpful to convert the C_n^2 results to some other measure that can more readily be compared to the telescope error budget, and to try to put them into the context of plausible building heights. The present plans call for the lower edge of the dome slit to be at 11.8 m above the ground, and for the primary mirror surface (in the zenith-pointing position) to be at 12.8 m. Before the SOAR Conceptual Design Review, the plans were for these to be at roughly 13.8 m and 15.1 m, respectively. Thus we are inquiring about the effect of changing these heights by 1-2 m within the 10-15 m height range.

To try to see the effect of moving the telescope height within this range, I first calculated the integrated C_n^2 above the lower edges of the upper two C_n^2 height bins. These lower edges are at 12m and 22m. This gives an estimate of the effect on seeing that arises from looking through the column of air from either of these heights up to 32m. I then used standard formulae for Kolmogorov seeing (Eqs. 3.1-10 and 1.3-2 from the Keck Bible) to convert the C_n^2 values to FWHM at $\lambda 0.5\ \mu$m. The results are shown as the individual points in Figure 8. The black diamonds are the FWHM contribution if the telescope were at 22m, while the red triangles are the FWHM contribution if the telescope were at 12m. The x-axis is again time in units of measurement number, and the thick vertical lines show the separation between nights (with only the data taken at night being shown here).

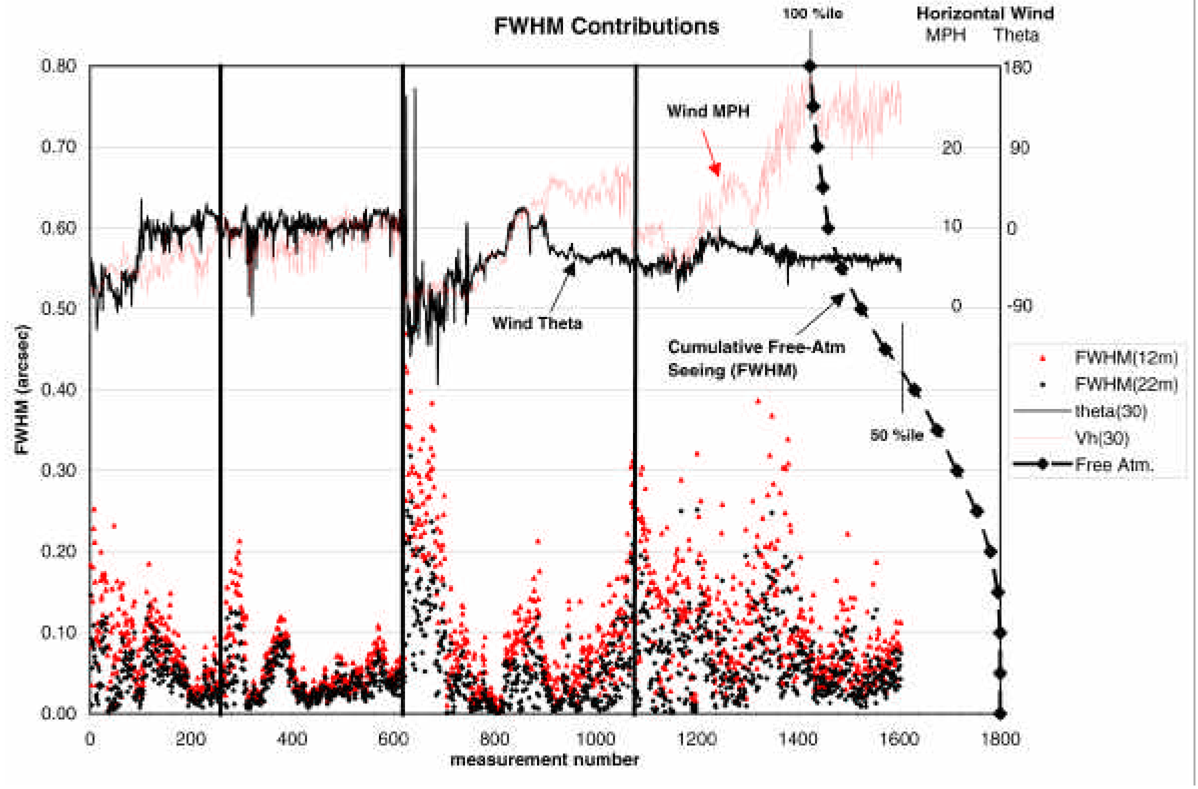

Fig. 8

The two wiggly lines across the top of the graph show the wind direction (black line) and speed (red line), with the scales given at the upper right edge of the plot. When the wind came from 0° (North) there was no difference in the seeing at the two heights. When the wind came from the more normal –30 to –45° (NW) the seeing from 12m did tend to be somewhat worse than the seeing from 22m, but this difference disappeared when the wind velocity increased from ~10 mph to ~25 mph. During the period at the start of night 3 (near measurement number 610) when the wind was swinging around through the south but with wind speed was ~0 mph, the seeing blew up as viewed from either height.

Almost all of the FWHM values shown in figure 8 are below 0.2 arcsec. This is consistent with the small values derived from the microthermal and echosonde measurements made from the Gemini site. These values must be compared to the other atmospheric seeing effects that the telescope will also be experiencing at the same time. The SCIDAR and balloon measurements made by the French team show that there is always significant "free atmosphere" seeing (defined as starting at 1 km above the site and integrated up to 23 km) which at Cerro Pachon has median r_0 = 24.1 cm (FWHM = 0.42 arcsec at λ0.5 µm). This is consistent with measurements from any other site; for example at Mauna Kea the median free atmosphere seeing is r_0 = 24.6 cm. There are bound to be additional contributions to the seeing coming from heights between 32m and 1km and at many sites these are larger than the free-atmosphere seeing. But the free-atmosphere seeing is at least a lower limit against which we should be comparing the benefits of changing the height of the telescope.

The draft report by Chun (his Figure 2) gives the distribution of FWHM values from the free atmosphere. The corresponding cumulative distribution is shown on Figure 8 as a heavy dashed line near the right edge of the figure. This cumulative distribution has been rotated 90° counterclockwise from the usual orientation in order to have its FWHM axis be the same as the one for the main plot. Therefore, the cumulative distribution has value 0 at the lower right corner (measurement number = 1800, FWHM = 0.00) and reaches a value of 1 at the top of the plot (measurement number = 1400, FWHM = 0.80).

I apologize for the complexity of Figure 8, but it is very useful to be able to see all of these data at the same time. Clearly, the free atmosphere seeing is almost never as small as the low-altitude seeing as represented by the individual points shown on the plot. That is, the low-altitude seeing usually is not significant.

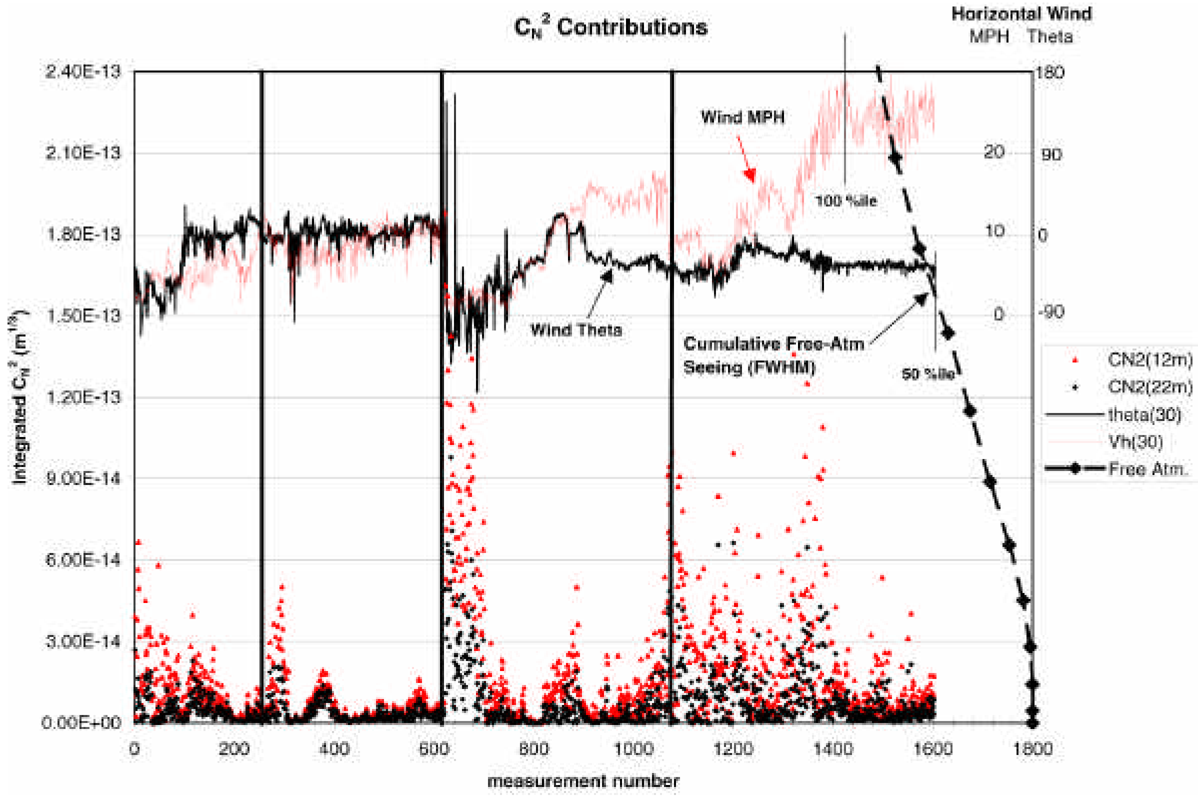

Fig. 9

There is one last figure to describe. Figure 8 shows the low-altitude seeing and the free-atmosphere seeing in terms of FWHM so that they can be compared to the telescope error budget. But these two seeing components must be combined by weighting them as $FWHM_{total} = [\Sigma(FWHM_i^{5/3})]^{3/5}$, which makes it difficult to compare them. Figure 9 is the same as Figure 8, except that the seeing values are now shown as C_n^2 components, which can be directly added to get the total C_n^2. This may make it easier to visualize the relative importance of low-altitude and free-atmosphere seeing. But remember that the total FWHM does not scale linearly with the total C_n^2, but rather as $(C_n^2)^{3/5}$.

6.0 Conclusions

- Only the 0-6m height range stands out as a particularly strong contributor to poor seeing (Figure 5, bottom panel). Once the telescope is above that height range, there will be steady but only modest improvements as it is placed higher.
- For any of the heights contemplated for the SOAR telescope, under the normal range of wind conditions, the effects of ground-level seeing are small compared to the free-atmosphere seeing that will be there anyway (Fig 8, 9).
- The small effect of the ground level seeing determined here is consistent with previous microthermal and echosonde studies from the Gemini site (Section 1.1).
- The present default heights are: bottom of dome slit at 11.8 m, telescope primary mirror at 12.8 m. Moving these higher will produce only slight improvements in the telescope performance under normal atmospheric conditions.
- The concern about the preceding statements is that they are based on only 4 nights of microthermal measurements, although there are 8 months of wind studies to show that these were taken under typical conditions.
- The telescope should be placed as close to the west edge of the ridge as is practical. This will effectively make the telescope “taller” relative to the airflow pattern (Fig 4).