Optical Seeing at Sierra Negra

Esperanza Carrasco, Alberto Carraminana, José Luis Avilés, and Omar Yam

Instituto Nacional de Astrofisica, Optica y Electronica, Luis Enrique Erro 1, Tonantzintla, Puebla 72840, Mexico; bec@inaoep.mx

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ABSTRACT. Optical seeing measurements carried out at Sierra Negra, the site of the Large Millimeter Telescope, are reported. The site, one of the highest peaks in central Mexico, offers good coverage of the northern and southern hemispheres, and we have undertaken several campaigns to investigate the astronomical potential of the site in the optical. Here we report on our campaign to establish the seeing quality of the site. We present data from the first three campaigns of optical seeing monitoring covering 2000 February to 2002 May, carried out with a Differential Image Motion Monitor. The results clearly indicate subarcsecond seeing, better statistics during the dry season, and no dependence on the time of night. We find no dependence of our results on the integration time used.

1. INTRODUCTION

Sierra Negra is an extinct volcano in the state of Puebla, Mexico, located at N18°59′06″ latitude, W97°18′53″ longitude, and an altitude of 4580 m above sea level. The mountain is next to Citlaltepetl, the highest peak in Mexico, with just 8 km separating both summits. Sierra Negra is about 100 km west of the coast of Veracruz on the Gulf of Mexico and 300 km from the Pacific Coast. The site, administrated by the Instituto Nacional de Astrofisica, Optica y Electronica (INAOE), is inside the Pico de Orizaba National Park. Easy access is available via a 100 km motorway from the city of Puebla followed by a 20 km access road to the summit. The journey from Puebla city takes about 2 hours.

In 1996 February, Sierra Negra was selected, from more than 20 potential sites, as the site of the Large Millimeter Telescope (LMT/GTM), now under construction. The decision was based on its low atmospheric water vapor content, with registered opacities at 240 GHz down to \( \approx 0.02 \). The LMT/GTM is a 50 m antenna optimized for 1–3 mm observations. First light and science operations are planned for 2005. The LMT/GTM is a bi-national project between Mexico and the United States, led by INAOE in Mexico and the University of Massachusetts, Amherst.

With the development of the Sierra Negra site, INAOE planned to measure the quality of the site for optical observations. Because of its altitude and location, the site is intrinsically very dry; therefore the conditions are likely to be favorable for near-infrared and optical observations. An unknown property of the site is its optical seeing, a key parameter in determining how good an astronomical site is. In the last few decades great efforts have been dedicated to the development of 8–10 m class diameter telescopes and for instrumentation that requires very precise site characterization. Furthermore, the new generation of extremely large telescopes will require the selection of sites with very good seeing conditions.

INAOE decided to undertake a first optical seeing and weather measurement campaign starting in 2000 February without the availability of basic facilities. A temporary setup was prepared for the February campaign, which was in fact the first astronomical nighttime work performed at the site. The second campaign started in 2000 October, with better facilities such as a 5 m tower, a container, a suitable power supply, and a place to rest—at about 3000 m above sea level—at observing. From 2001 May we started a routine measurement regime. Here we present the results obtained from 2000 February to 2002 May. Weather data have been taken almost continuously from 2000 November to the present. The weather analysis will be reported elsewhere.

2. THE INSTRUMENT

The data for this work were taken with a Differential Image Motion Monitor (DA/IAC DIMM) developed by Vernin & Muñoz-Tuñón (1995), based on the same physical principle as the ESO DIMM (Sarazin & Roddier 1990) but commercialized by the French company LHESA. The DIMM principle is to produce twin images of a star with the same telescope via two entrance pupils and a wedge. The instrument consists of a 20 cm Celestron telescope, on a very robust equatorial mount, with an intensified CCD camera coupled via an optical fiber bundle to the CCD, a Matrox frame grabber board, and a PC. The two \( D = 60 \) mm apertures, separated by a distance \( d = 140 \) mm, are located on a mask attached to the telescope entrance pupil. A precisely cut wedge placed over one of the pupils splits the incoming light, separating the two star images by approximately 30°. The intensified CCD camera and the frame grabber register the relative position of both stellar im-
Fig. 1.—Layout of the Large Millimeter Telescope (LMT) site. North is up, and east is to the right. The LMT track is marked by the 40 m diameter dark circle located at the middle left. The approximate location of the seeing monitor and weather station is marked by the black square, east-northeast of the LMT construction.

ages after computing the centroid position of each. A statistical seeing value is assessed on the basis of the variance of the differential image motion after 200 images are taken. The measurement corresponds roughly to a wavelength $\lambda = 0.5 \, \mu m$, as dictated by the response of the system.

Because it is a differential method, the technique is, in principle, insensitive to erratic motions of the telescope introduced by wind or ground vibrations. Sarazin & Roddier (1990) showed that, assuming a Kolmogorov power-law spectrum for the turbulent cells, the longitudinal and transverse variances of the differential motion between the images, $\sigma_l$ and $\sigma_t$, are related to the Fried parameter $r_0$ as

$$\sigma_l^2 = 2r_0^2 \lambda^{-5/3}(0.179D^{-1/3} - 0.097d^{1/3}),$$

$$\sigma_t^2 = 2r_0^2 \lambda^{-5/3}(0.179D^{-1/3} - 0.145d^{1/3}).$$

Two independent $r_0$ values are obtained that, in principle, should have the same value. The parameter $r_0$ can be thought of as the telescope diameter that would produce a diffraction spot of the same size as that produced by the atmospheric turbulence. The seeing is given by $s_{FWHM} = 0.98(\lambda/r_0)$. These computations are carried out internally by the instrument, providing measures of $s = s_{FWHM}$ derived from the longitudinal and transverse estimates. The DA/IAC DIMM achieves an accuracy better than $0.1$ for stars brighter than fourth magnitude with a 10 ms time exposure. A reliable seeing measurement is attained within 20 s.

3. OBSERVATIONS AND DATA

The seeing monitor location at the summit is shown in Figure 1. The LMT is located to the left. The circle corresponding to the LMT track is marked and is 40 m in diameter. The approximate location of the seeing monitor and weather station is marked by the black square, east-northeast of the LMT. The DIMM and the weather station are on a 5 m tower to avoid the surface layer (Vernin & Muñoz-Tuñón 1994). The DIMM is on a tower independent of the platform, where observers can move freely without affecting the seeing measurement. The tower is near a sharp edge to face directly into the incoming winds. Thermal equilibrium is ensured by the absence of an enclosure.

The data available cover 85 nights, grouped in three sets: four nights between 2000 February 22 and April 7, corresponding to the first campaign; a second campaign with 10 observing nights between 2001 October 23 and December 13; and a third campaign that consisted of 71 nights from 2001 May 24 to 2002 May 3. We observed bright stars, almost always $m_V \approx 2.5$. 

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Fig. 2.—Seeing daily statistics for all data points. The dots are the median and the error bars span the first to third quartiles. The central dotted line denotes the seeing median for the whole data set, corresponding to 0′.78. The top dotted line is the distribution third quartile, equal to 1′.04, and the bottom dotted line is the first quartile, corresponding to 0′.61.

Fig. 3.—Histogram (top) and cumulative (bottom) seeing distribution of all data points. The global statistics show that for 85 observing nights spanning 2000 February to 2002 May, seeing values of 0′.61 were achieved 25% of the time, seeing below 0′.78 for 50% of the time, and subarcsecond seeing 70% of the time.

TABLE 1
GLOBAL MONTHLY STATISTICS

| DATE       | Nights | Hours | Points | Mean (arcsec) | σ (arcsec) | Min (arcsec) | q1 (arcsec) | Median (arcsec) | q3 (arcsec) |
|------------|--------|-------|--------|---------------|------------|--------------|-------------|----------------|-------------|
| 2000 Feb ... | 1      | 0.3   | 42     | 0.756         | 0.087      | 0.606        | 0.689       | 0.748          | 0.795       |
| 2000 Mar ... | 1      | 1.2   | 227    | 0.541         | 0.077      | 0.397        | 0.488       | 0.531          | 0.586       |
| 2000 Apr ... | 2      | 1.5   | 205    | 0.650         | 0.132      | 0.482        | 0.578       | 0.631          | 0.696       |
| 2000 Oct ... | 2      | 2.3   | 389    | 1.035         | 0.344      | 0.460        | 0.744       | 0.958          | 1.259       |
| 2000 Nov ... | 2      | 3.5   | 427    | 0.701         | 0.204      | 0.290        | 0.553       | 0.678          | 0.824       |
| 2000 Dec ... | 6      | 25.5  | 2383   | 0.661         | 0.354      | 0.238        | 0.401       | 0.506          | 0.894       |
| 2001 May ... | 2      | 1.7   | 302    | 0.887         | 0.204      | 0.552        | 0.722       | 0.854          | 1.021       |
| 2001 Jun ... | 3      | 7.5   | 1178   | 0.910         | 0.468      | 0.466        | 0.749       | 0.848          | 0.965       |
| 2001 Jul ... | 4      | 12.0  | 1926   | 0.736         | 0.374      | 0.229        | 0.488       | 0.670          | 0.870       |
| 2001 Aug ... | 8      | 26.7  | 4467   | 1.589         | 0.602      | 0.476        | 1.172       | 1.489          | 1.894       |
| 2001 Sep ... | 2      | 6.0   | 1063   | 0.783         | 0.307      | 0.329        | 0.576       | 0.677          | 0.857       |
| 2001 Oct ... | 3      | 15.2  | 2009   | 0.811         | 0.258      | 0.376        | 0.616       | 0.789          | 0.962       |
| 2001 Nov ... | 9      | 37.6  | 7352   | 0.826         | 0.312      | 0.290        | 0.622       | 0.776          | 0.959       |
| 2001 Dec ... | 7      | 37.5  | 6380   | 0.835         | 0.326      | 0.343        | 0.614       | 0.755          | 0.963       |
| 2002 Jan ... | 4      | 29.6  | 3837   | 0.782         | 0.342      | 0.326        | 0.574       | 0.679          | 0.840       |
| 2002 Feb ... | 6      | 36.0  | 4207   | 0.861         | 0.404      | 0.272        | 0.602       | 0.758          | 1.002       |
| 2002 Mar ... | 9      | 36.1  | 4867   | 0.980         | 0.431      | 0.293        | 0.669       | 0.846          | 1.203       |
| 2002 Apr ... | 10     | 44.1  | 7616   | 0.788         | 0.284      | 0.274        | 0.588       | 0.742          | 0.913       |
| 2002 May ... | 4      | 17.9  | 3202   | 0.972         | 0.447      | 0.347        | 0.675       | 0.834          | 1.100       |

All data ... 85 342.1 52079 0.898 0.441 0.229 0.615 0.784 1.046

Note.—Equal weight is given to each seeing measurement.
The high altitude and precarious initial development of the site made the initial runs a real challenge. Nevertheless, we successfully carried out measurements, for the first time, during the night at the summit. To compare all measurements, we present statistics giving equal weight to every data point. For the analysis we consider only data files with at least 20 points acquired close to the zenith (air mass $\leq 1.15$) with nonsaturated images (DIMM parameter pixmax $\leq 255$) to ensure a reliable stellar centroid determination.

3.1. Results on Seeing Statistics

Figure 2 is the daily plot of all the measurements. The dots are the median and the error bars span the first to third quartiles. The central dotted line denotes the seeing median for the entire data set, corresponding to 0\textquoteright 78. The top dotted line is the distribution third quartile, 1\textquoteright 05, and the bottom dotted line is the first quartile, corresponding to 0\textquoteright 62. The histogram and the cumulative distribution of the same data are shown in Figure 3. Subarcsecond seeing is achieved 75% of the time.

To investigate the seeing seasonal behavior, we define the dry season from November to April and the wet season from May to October. The histogram and cumulative distribution for the dry and wet seasons are shown in Figures 4 and 5, respectively. While the seeing median during the dry season is
Fig. 7.—Seeing time profiles for 12 nights with samples of 15 seeing measurements taken by alternating 10 and 20 ms integration times. Each point in the figure represents the median over each sample, distinguishing between 10 ms samples (filled circles) and 20 ms samples (open circles). There is no clear qualitative systematic difference between both sets of data, all taken in 2001.

0.75, for the wet season it increases to 0.92. However, it should be noted that during 2001 August the seeing was especially bad (with a median of 1.49; see Table 1). To study the August contribution to the seeing, we calculated statistics for the wet season without 2001 August; the seeing median becoming 0.78, significantly closer to the dry season seeing median.

To compare the monthly seeing behavior, in Table 1 we present statistics giving equal weight to each seeing measurement for the complete data set: the first column is the month, and the next three columns give the details of the data acquired: number of nights, number of observing hours during those nights, and number of points. The next columns give the data statistics: mean, standard deviation, minimum value, first quartile, median, and third quartile. The global statistics show that for 85 observing nights spanning 2000 February to 2002 May, the seeing median is 0.78 with a standard deviation of 0.44.

In Figure 6 the distribution of seeing values as a function of UT is shown for the 85 observing nights. The dots represent the median for each hour, and the error bars span the first to third quartiles. The histogram is shown in the upper panel. It must be noted that the first bin, corresponding to 7–8 P.M. local time, has only a few points, so the high seeing value
might be due to low number statistics rather than intrinsically higher seeing at the beginning of the night. We conclude that our data do not show any systematic trend throughout the night. Muñoz-Tuñón, Vernin, & Varela (1997) observed that there is no general trend in the seeing evolution for the Roque de los Muchachos Observatory. In contrast, Giovanelli et al. (2001) point out that for high-altitude cordillera sites in northern Chile, the seeing tends to be of lower quality at the beginning of the evening.

3.2. The Seeing Integration Time

Several authors have discussed that the temporal averaging of the variance of the differential motion with a finite exposure time depends on the average velocity and the direction of displacement of the wave-front corrugation with respect to the DIMM aperture (Martin 1987; Sarazin & Tokovinin 2001). Giovanelli et al. (2001) measure the seeing by alternating 10 and 20 ms exposures for high-altitude cordillera sites in Chile. They obtain seeing estimates derived from 10 ms exposures, 20 ms exposures, and extrapolations to “zero exposure,” obtained by multiplying the 10 ms seeing by the ratio of the 10 and 20 ms measurements. They find that the median values vary between 0.66 and 0.76 for the 0 ms seeing, between 0.56 and 0.65 for the 10 ms seeing, and between 0.48 and 0.56 for the 20 ms seeing. According to these authors, the seeing for the 10 ms series is statistically worse than that for the 20 ms series, as the latter smears the image motion somewhat.

Our DIMM has a default integration time of 20 ms. The first data set that spans 2000 February to 2001 August was taken using that integration time. During the next 12 observing nights, we alternated measurements with 10 and 20 ms integration times. The camera control allows the user to alternate between the default time and a mechanically selected integration time. As the selection is manual, we decided to take 15 integrations at each integration time. The results are shown in Figure 7, where the seeing as a function of time is shown for each night. The filled circles correspond to the medians of the 10 ms integration samples, while the open circles to the medians of the 20 ms samples. Qualitatively, there is no significant difference between the trends of both data sets. We compare the samples quantitatively by plotting the 10 ms seeing medians versus 20 ms seeing medians where each data set has been interpolated through a spline fit to overlap the other data set in time, such that at each time we have one data point (from the 10 or 20 ms sample) and one spline interpolation (from the 20 or 10 ms sample) that can be compared. The comparison is shown in Figure 8, where the best fit to the data is the dotted line and the solid line represents $s_{10} = s_{20}$. The best-fit slope $(0.89 \pm 0.20)$ and intercept $(0.10 \pm 0.15)$ are compatible with $s_{10} = s_{20}$.

We also compared the complete distributions of 10 ms and 20 ms integration time seeing values, shown in Figure 9. A $\chi^2$ comparison test between both distributions gives $\chi^2 = 64.8$ for 46 degrees of freedom, that is, a 3.5% probability that both distributions are the same. However, if we compare both distributions with the common distribution, derived from combining the samples, then the respective $\chi^2$ values are 10.1 and 12.1 for the same number of degrees of freedom, giving respective probabilities of $1 - (4 \times 10^{-6})$ and $1 - (1 \times 10^{-1})$ that each distribution can be derived from the same parent distribution. As seen in the two lower panels of Figure 9, the two distributions of seeing values are compatible with a single parent distribution. The total seeing median including both integration times is 0.77.

Following a suggestion by Marc Sarazin (private communication), we studied the presence of temporal averaging effects on our seeing measurements by comparing the seeing median versus the wind velocity at 200 mbar using the NOAA Global Gridded Upper Air database, for each night of our 20 ms sample. The results are shown in the upper panel of Figure 10. The seeing error bars span the first to third quartiles. The wind data are daily averages of four measurements available on the NOAA database. The dotted line represents the best least-squares linear fit, consistent with slope equal to zero within 1.1 σ. The correlation coefficient is equal to $-0.227$ and the rms dispersion is 0.359. The errors were obtained using a bootstrap technique. The data show that the seeing does not drop at high speed as would be expected in the presence of temporal...
averaging effects. In the lower panel of Figure 10, the 10 ms seeing data are shown. In this case the best fit is also consistent with zero slope, within 1.5 \( \sigma \), and the correlation coefficient is \(-0.274\).

To study the presence of any correlation between seeing and wind velocity at ground level, we compare the seeing and wind velocity daily medians at the site. The wind velocity was measured with a meteorological station located on the seeing monitor tower. Figure 11 shows the seeing median as a function of the wind velocity median for those nights that have simultaneous seeing and wind velocity data. The seeing error bars span the first to third quartiles. The wind velocity distribution median was calculated from the data obtained between 8 p.m. and 6 A.M. local time; the error bars corresponding to the first and third quartiles are not included in the plot for clarity. In the upper panel the results for 17 nights of the 20 ms sample are shown. The dotted line represents the best fit that is consistent with zero slope within 1.4 \( \sigma \), a correlation factor of \(-0.435\), and an rms dispersion of 0.384. In the lower panel the data obtained for 50 nights of the 10 ms sample are shown. The best fit is consistent with slope equal to zero within 1.1 \( \sigma \), a correlation factor of 0.281, and a rms dispersion of 0.256.

In contrast to the results of Giovanelli et al. (2001) for high-altitude cordillera sites in Chile, the data for Sierra Negra suggest that, for our statistics, there is no difference between the 10 and 20 ms series. It must be noted that Vernin & Muñoz-Tuñon (1995) find the seeing bias produced by the difference in exposure time to be highly dependent on the magnitude of the star. As we generally use stars brighter than \( m_V = 2 \), it is possible that this bias is in our data but below the measurable error and therefore does not influence our results. Nevertheless...
Fig. 10.—Seeing median as a function of the wind velocity at 200 mb. The seeing error bars span the first to third quartiles. The daily average wind velocities were obtained from the NOAA Global Gridded Upper Air database. Seeing data for the 20 ms sample (top): the dotted line represents the best linear fit, slope = $-0.009 \pm 0.008$, consistent with zero slope within 1.1 $\sigma$. The correlation coefficient is $-0.274$, and the rms dispersion is $0.0260$. Seeing data for the 10 ms sample (bottom): the best linear fit, slope = $-0.006 \pm 0.004$, is consistent with zero slope within 1.5 $\sigma$. The correlation coefficient is $-0.227$, and the rms dispersion is $0.0359$.

Fig. 11.—Seeing median as a function of the wind velocity median at ground level for those nights that have both seeing and wind velocity data. The seeing error bars span the first to third quartiles, while the wind velocity error bars are not included for clarity. Seeing data for 17 nights of the 20 ms sample (top): the dotted line represents the best linear fit, slope = $-0.06 \pm 0.04$, consistent with zero slope within 1.5 $\sigma$. The correlation coefficient is $-0.435$, and the rms dispersion is $0.384$. Seeing data for 50 nights of the 10 ms sample (bottom): the best fit, slope = $0.03 \pm 0.03$, is also consistent with zero slope within 1.1 $\sigma$. The correlation coefficient is $0.281$, and the rms dispersion is $0.256$.

from 2001 December onward, all our measurements are made using 10 ms exposures.

4. CONCLUSIONS

We present the first seeing measurements carried out at Sierra Negra. For 85 observing nights, seeing values of 0.61 were achieved 25% of the time, below 0.78 during 50% of the time, and below the subarcsecond level for 70% of the time. The comparison between the dry and wet seasons shows that the seeing median is better during the dry season, with a value of 0.73 and subarcsecond seeing 77% of the time. In contrast, for the wet season the seeing median value of 0.92 is strongly affected by the 2001 August contribution. We analyzed the dependence of the seeing statistics on time of night and found no systematic trend of seeing as a function of time. We did not find any correlation between the seeing values and the 200 mbar wind velocity. A preliminary analysis of the correlation between the seeing and the wind velocity at ground level was carried out. The results show that there is not an obvious correlation between them. Nevertheless, we will continue to analyze the seeing as a function of other meteorological parameters in more detail to try to find out where most of the turbulence is concentrated.

The results obtained so far show that Sierra Negra is a competitive site for optical astronomy. We will continue our seeing and meteorological measurements to characterize the site on a longer timescale basis. We have carried out an independent analysis of the seeing temporal structure, and the results will be reported in a separate paper.

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