Adaptive Optics and Interferometry in the 21st Century
ASP Conference Series, Vol. 174, 1999
S. Restaino, W. Junor, and N. Duric, eds.

Characterization of Atmospheric Turbulence at Four Mesa-Top Sites in New Mexico

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Abstract.
Traditional astronomical sites are generally associated with high, relatively isolated mountain peaks. Their selection is driven by constraints of light pollution, cloud cover and water vapor considerations. These constraints make sense in the context of traditional astronomy where light-gathering power is the overriding consideration.

Consideration of image quality and high spatial resolution presents a different constraint, that of atmospheric turbulence. In this case, the qualities that make mountain peaks excellent conventional sites are undermined by the fact that such summits generate their own atmospheric turbulence. Thus, the traditional model of a tall mountain peak is not necessarily an ideal one when considering astronomical telecopes that are designed for high spatial resolution.

Instruments such as AO-equipped telescopes and optical interferometers may well require alternate sites because minimizing turbulence is a higher priority than altitude and water-vapor considerations. Furthermore, optical/IR interferometers require an area approximately one kilometer in diameter with minimal topological relief. One possible type of site is a mesa where prevailing winds may form laminar flows as they interact with the wind-facing edge of the mesa top. An astronomical telescope, or array, located on the windward edge of a mesa top may experience relatively little turbulence compared to a traditional mountain peak.

This paper describes atmospheric evaluations of four mesa-top sites in western New Mexico. The characterization of the turbulence is presented in absolute terms, followed by a comparative analysis of the four sites. It is found that the highest quality sites (those with minimal surface turbulence) are those which lie on the windward edges of the mesas.

1. Introduction

The motivation for testing and ultimately developing a new astronomical site in western New Mexico arises from the LodeStar project, a New Mexico - based program for public education and outreach. A major component of this federally funded project is the development of Enchanted Skies Park, an extensive, public-access astronomical site devoted to both education and research.

1.1. Required Characteristics of a New Observatory Site

To fulfill the purpose of both the educational and research missions of Lodestar a list of required and desirable characteristics of a new observatory site was drawn up. We tabulate below a series of criteria that were used in the selection and ranking process. We begin with our quantitative criteria followed by a list of practical requirements and concluded by a list of desirable quantities.

Quantitative Measures. In order for an astronomical site to be scientifically valuable it must satisfy a number of quantitative criteria. These are listed below:

- The site must have an elevation of at least 7000' in order to minimize the effect of the atmosphere on observations. At these elevations the site rises above the planetary boundary layer, a major source of atmospheric turbulence and absorption (e.g. Beckers, 1993).

- The site must have sufficient surface area to accommodate a 1 km diameter (or greater) array of telescopes. Justification for the development of a large site and the associated infrastructure investment is based on consideration of future developments in optical/IR interferometry. As interferometer technology evolves and the possibility of kilometer-scale baselines grows it is necessary to ensure that the future viability of the site is not compromised. Thus, the development of a large kilometer-scale site will ensure that it can accommodate interferometers of the future. A two kilometer distributed array, for example, is capable of $1''$ resolution at a wavelength of 1μ. Such an array concept provides a long-term scientific goal of unprecedented science potential (e.g. Ridgway, 1989).

- The site must have surface relief of less than 100' over flat 1 km by 1 km areas.

- The presence of a cliff or bluff facing the prevailing wind with no upwind obstructions for at least several tens of miles is optimal for minimizing the effects of an atmospheric boundary layer (also called the surface layer). The surface layer is the greatest local source of turbulence, so choosing the right site can eliminate most of its effects.

- The skies in the area should be free of clouds for the largest possible number of nights per year.
- The skies should be largely free of light pollution. The site cannot be too close to a major urban center.

Practical Requirements. There are additional practical requirements that make a site useful.

- The site should be accessible for all-day, year-round use by scientists and the public. A site that is snowed in for significant amounts of time is therefore not practical.
- The site should not be prohibitively far from Albuquerque, from where many educational groups will travel.

Desirable Qualities. There are qualities that are not strictly required but are desirable.

- The site should be surrounded by open land or similarly protected from the effects of development which would compromise the scientific quality of the site, especially light pollution.
- The site should simplify night time operation so that it is safe for scientists and educational groups.

2. The Initial Selection Process

Topographic data covering the entire state of New Mexico were obtained and placed into a database. This first selection criterion was used to generate a list of all sites in New Mexico with elevations greater than 7000'. The quantitative and practical criteria were then applied to that list to narrow the candidate field.

These requirements eliminated several well known sites. For instance, the Sandia Crest is largely unavailable because of the wilderness area, undesirable because of the light pollution from Albuquerque, not flat enough to accommodate a 1 km array, and often covered with orographic clouds when other sites are clear. South Baldy, in the Magdalena Mountains, though already a scientific preserve, does not have a flat, 1km square surface and is frequently snowed in, presenting difficult access issues in the wintertime. It also suffers from orographic effects as evidenced by the presence of a major lightning laboratory.

The sites that satisfied a majority of the criteria are listed below.

- Mesa Negra
- Horace Mesa
- Putney Mesa
- Chicken Mountain
- Mesa Gallina

All of the above sites were then visited to determine first hand the amount of useful space and the quality of the terrain. These on-site inspections revealed that Chicken Mountain and Mesa Gallina failed on three of the major criteria - not enough flat area on top, not enough clear upwind fetch and lack of access. In addition, Putney Mesa was found to be unsuitable because of its small size and lack of access. It is a very remote site, would be expensive to develop and would inhibit visitors because is is so far from the beaten path. Furthermore, its proximity to a National Conservation Area makes it additionally difficult to construct an access route. With three of the contenders removed the only remaining candidates that satisfied our criteria were Mesa Negra and Horace Mesa. The former is flat enough and just big enough to support the project. The latter is as flat but much larger. Consequently we examined three sites on Horace Mesa. There is, therefore, a total of four sites, or combinations of sites, that could support Enchanted Skies Park. In the following sections we describe an intensive scientific study of the four sites aimed at evaluating their suitability for the LodeStar project. In the last section we list the four sites in decreasing order of preference.

The selection process that led to these four sites is summarized below.

Location	Adequate Area?	Flat Top?	Upwind Fetch?	Access Safety?	Utilities?	Local Personnel?
Chicken Mnt	No	No	Poor	Poor	No	Unknown
Horace Mesa	Yes	Yes	Excellent	V Good	Electric/Gas	Yes
Mesa Gallina	No	No	Poor	Poor	No	Unknown
Mesa Negra	Yes	Yes	Excellent	Fair	No	Limited
Putney Mesa	Yes	Yes	Excellent	Poor	No	Limited

3. Field Testing

The geographical proximity of the sites to each other simplifies the prediction of general weather because storm patterns and jetstream flows are the same for all four of them. We have, therefore, concentrated on measuring the turbulence characteristics of the four sites because turbulence can be a very local effect. Atmospheric turbulence is the only reason why ground-based telescopes cannot reach the kinds of angular resolution achievable by the Hubble Space telescope. Consequently, the quality of an astronomical site is characterized not only by the number of clear nights but also by the stillness of the air above it. For a site on which high-resolution astronomical imaging is to be performed, the turbulence issue is of paramount importance.

There are three major layers in the atmosphere that contribute to turbulence. The first is the surface layer. This is a layer lying close to the surface, varying in depth from 50 - 150 feet. It is defined by local conditions such as wind direction, diurnal heating cycles and topography of the terrain. A site can be chosen to minimize the effects of this layer. The surface layer can be quantified using microthermal devices, as described below. The planetary boundary layer is the result of global wind patterns and terrain. It is generally less than 1 km above sea level. It can be avoided simply by choosing a site that is more than a kilometer in elevation. Our 7000' criterion puts all our sites safely above the planetary layer. The third layer is the high wind shear region in the tropopause. This layer is located about 10 km above the sea level, higher than any mountain peak in the world. It cannot, therefore, be avoided. Because of its great height, its effect is essentially the same for all sites in New Mexico. Thus, all four of the sites studied are affected equally by this layer. Consequently, the only layer we have any control over is the surface layer. We have performed extensive measurements of the turbulence associated with this layer in order to identify the site with the stillest air.

4. Atmospheric Turbulence

We begin by describing some basic theory of atmospheric turbulence, thereby setting the context within which to interpret our microthermal measurements. The microthermal measurements are described in 4.2. Finally, measurements of turbulence caused by the entire atmosphere are described in 4.3.

4.1. Theory

Turbulence on scales of a few centimeters to a few meters leads to small differences in air temperature on the same scales. The temperature differences, on scales of $\vec{r}$ are characterized by the temperature structure function,

$$D_t = \langle |T(\vec{\rho}+\vec{r}) - T(\vec{\rho})|^2 \rangle_r \;\; K^2 \tag{1}$$

where $\vec{\rho}$ represents the location of the measurement and $\vec{r}$ is the separation of a pair of probes. The turbulence has a dependence on the scale length, $\vec{r}$, and is often characterized as Kolmogorov turbulence, in which case,

$$D_T(|\vec{r}|) = C_T^2 |\vec{r}|^{2/3} \; K^2. \tag{2}$$

It is also possible to define the structure function for refractive index variations, such that,

$$C_n^2 = \left(\frac{7.8 \times 10^{-5} P}{T^2}\right)^2 C_t^2 \tag{3}$$

where T and P are ambient temperature and pressure, respectively. Combining equations 1,2 and 3 yields:

$$C_n^2 = 7.8 \times 10^{-5} \left(\frac{P}{T^2}\right) \frac{\langle |T(\vec{\rho}+\vec{r}) - T(\vec{\rho})|^2 \rangle}{|\vec{r}|^{2/3}}, \tag{4}$$

Equation 4 represents the relationship between the structure function and the temperature variations we measured using microthermal devices (as explained below). The structure function is in turn related to standard measures of turbulence, as follows:

The effect of turbulence on a wavefront (say from a star) incident on the telescope is to distort it. This distortion leads to the blurring of the image that is formed at the focus of the telescope. The distortions are characterized by the *phase* structure function,

$$D_\phi(x) = \langle|\phi(y+x) - \phi(y)|^2\rangle_y = 6.88 r_0^{-5/3} x^{5/3}\ rad^2. \quad (5)$$

The variables x and y characterize the plane of the telescope aperture. The parameter r_0 is itself defined via

$$r_0^{5/3} = 0.423\lambda^2 \int C_n^2(z)dz \quad (6)$$

where λ is the wavelength of the radiation and the square of the structure function is integrated over altitude, z, above the site.

The quantity, r_0 characterizes the extent over which a wavefront maintains coherence in the plane of the telescope aperture. The quantity, C_n can be measured using microthermal devices to measure the temperature variations and applying equation 4.

4.2. Microthermal Measurements

Sites on Horace Mesa and Mesa Negra were chosen for detailed, long-term field testing for comparative studies of the astronomical properties of the atmosphere above the sites. Because the sites are separated by only a few tens of kilometers, the effects of the upper atmosphere are likely to be identical, so testing concentrated on the properties of the lower atmosphere, particularly the search for a turbulent surface layer.

The microthermal devices consist of a pair of resistance thermometers or probes. Commercially-produced probes were prohibitively expensive, so undergraduate students were employed to make probes by removing the glass envelopes from Sylvania Model 3S6/5-120V light bulbs. Careful removal allowed the filaments to be used as fast-time-response resistance thermometers. Each filament was stored in room air for a day and its resistance monitored until the effects of rapid oxidation tapered off, resulting in a constant resistance. Filaments were paired with others of similar resistance (within 5 ohms) thereby producing a pair of sensors with very similar characteristics. The tungsten/moly conductor interfaces were dipped in silver print (conductive paint) to stop further oxidation and provide improved strength. Each was then soldered onto its own 5 cm piece of rigid coaxial cable for physical and electrical connection. The other end of the rigid cable was connected to an electronic package by length of flexible RG-50 coaxial cable and an SMA connector.

Weather data were recorded continuously using portable weather stations. This allowed for a contiguous record of temperature, pressure, wind speed and wind direction. The temperature and pressure data were needed to convert the microthermal measurements into estimates of the coherence length of the surface layer, as described below.

The electronics package associated with the microthermal probes was designed to calculate the RMS temperature difference of the pair of probes at one minute intervals thereby determining the variance of the temperature (as described by equation 1). Rigid mounts of several sizes were constructed to allow probes to be separated by as little as 20 cm or as much as 150 cm, thereby evaluating Equation 1 for various values of $|\vec{r}|$. Use of Equation 4 along with our weather data allowed us to convert the temperature variance into C_n^2. Use of equation 5 then yields estimates of r_0 for the surface layer of the atmosphere.

The microthermal devices were mounted at various heights on towers to sample a significant column of air. Ideally the towers are small enough to be erected manually on remote sites but large enough to sample the atmosphere up to the height at which other types of instruments, acoustic sounders for example, can be used. Sound travel time considerations limit the latter type of instruments to determination of atmospheric structure at heights of about 20 meters and greater. Thus, each test site was equipped with a tower capable of holding microthermal devices at heights up to 20 meters. Additional 10 meter towers were erected for determining variations in C_n^2 and r_0 over ground separations as small as 20 meters.

Examples of r_0 measurements, made in this manner, are shown in figure 1 plotted as a function of local time over a period of two weeks. The most obvious feature of these measurements is the diurnal variation. The r_0's clearly drop almost to zero during the day, most likely because of convective heating which is particularly strong in the desert environment. The nighttime r_0's are quite variable but typically lie in the range of 30 cm - 100 cm for the Horace 1 site. As shown later, the other sites do not fare as well, Horace 3 showing the worst characteristics with typical r_0's in the 5 - 50 cm range. A formal comparison of the four sites is made in section 5.

The values of surface r_0's, quoted above, are much greater than the total r_0's (surface + upper atmosphere) measured at most mountain-based astronomical sites in New Mexico. Since the turbulence associated with the upper atmosphere should not, on average, vary strongly across the state we deduce that the surface layer is not the limiting factor in determining the total r_0's for the mesa-top sites. To confirm this deduction we performed some measurements of the total r_0, as discussed below.

4.3. The ATMOS Measurements

In order to obtain an empirical estimate of the turbulence along a line of sight passing through *all* of the atmosphere, it is necessary to monitor sources external to the atmosphere. One way to do this is to monitor the differential image motion of stars. The translational image motion measures the tipping and tilting of the wavefront caused by the turbulence. However, there are higher order distortions which cause the image to be spread out into a what is known as the "seeing disk". The latter can only be measured by freezing images on short ($< 0.01s$) time scales. The ATMOS machine is designed to do this type of measurement (Eaton, Hines and Hatch, 1995). It splits the light of a star as it enters the telescope and images two stellar images onto a fast-readout CCD camera. The two images are separated spatially by about 15 cm. Any relative motion between the images is the result of a breakdown in coherence between the two columns of air the stellar light is traversing. The amplitude of motion, combined with a model of the higher-order distortions, yields a measure of the coherence scale length, r_0, which is the largest radius on the aperture which is spatially coherent (ie the largest aperture that can produce a diffraction-limited image).

The ATMOS machine has been used at other existing observatory sites including Kitt Peak, Mt. Hopkins, Apache Point and Mauna Kea. Measurements made by this technique are recognized by the astronomical community as accurate, robust, and a valid indicator of site quality. It is fully described by Eaton, Hines and Hatch (1995).

The ATMOS measurements were made on the nights of November 7/8 and November 8/9, 1995. The equipment was set up at longitude W107^o 43' 33.2", latitude N35^o 05' 27.5". Measurements were made and r_0 calculated every minute. The values of r_0 varied from about 4cm to about 20 cm. The upper end of the distribution is unexpectedly good because it much higher than the 8 to 10 cm that is typical of mountain sites in New Mexico. Sample data are shown in Figure 3.

Tha above data were compared to the microthermal data (see Figure 1). It is apparent that the surface r_0's (as obtained from the microthermal measurements) are, on average, greater than the total r_0's obtained with ATMOS. The range of r_0 shown indicates that even when the surface layer dominates, the seeing is very good (r_0's of 15 cm are considered unusually good). However, the many data points that lie above the diagonal line indicate that the surface layer is less turbulent than the atmosphere above it. We conclude that the surface layer is not the limiting factor in determining the seeing conditions on Horace Mesa and that when the upper atmosphere is stable, astronomical seeing at this site can be exceptional.

This finding is important in light of of the study of Walters et al (1990) who find that the two flat sites they studied had poorer seeing tham typical mountain tops.

5. Site Comparison

With the above data in hand, we compared the four sites for the purpose of determining which would best serve the mission and purpose of the LodeStar project. The most critical comparison was that between Horace 1 and Mesa Negra sites because they sit on distinctly separate mesa tops. Simultaneous r_0 measurements at the two sites were available for the months of October and November of 1995. We constructed a histogram of the difference between the r_0 for the Horace 1 site and the Mesa Negra site from all the measurements available for each month. Sample histograms are shown in figure 3. Positive values indicate that Horace 1 is better, negative values indicate that Mesa Negra is better. It is clear that the the histogram is not centered on zero and is shifted toward positive values, indicating that most of the time, the Horace 1 site has superior turbulence characteristics. For the month of October, 1995, for example, there were 9,679 simultaneous measurements of r_0 at the two sites. Of these, 6,401 indicated a higher r_0 for Horace 1 while 3,294 measurements indicated that Mesa Negra was better. Statistically, the Horace 1 site is better twice as often as the Mesa Negra site that month. The difference is not as great for the month of November but Horace 1 still fares better.

We have made similar comparisons among the three sites on Horace Mesa, as shown in figures 5 and 6. The histograms represent maximum overlap of simultaneous measurements for each pair of sites. The histograms represent r_0 differences for Horace 1 - Horace 2 and Horace 3 -Horace 1. Thus, negative values indicate the Horace 1 site has the higher (better) r_0.

It is interesting to note that these results are consistent with the idea that windward edges of isolated mesa tops present laminar flows of air. The fact that the southwestern corner of Horace Mesa has consistently better seeing than the interior of the mesa suggests that the laminar flow breaks down less than four kilometers from the mesa edge. The data show that despite the identical weather and geographical conditions of the four sites surveyed the turubulence characteristics are determined locally, on scales of kilometers or less.

6. Summary

There have been very few studies specifically aimed at identifying interferometer sites. Examples include, those of Panel (1989), Walters et al (1990) and Tsay et al (1990). We have added data on four new sites to the short list of interfermoter sites.

On the basis of our study of four mesa-top sites in western New Mexico we conclude that the Horace sites, 1 and 2, are better than the Mesa Negra site. Of the Horace Mesa sites, Horace 1 better than Horace 2 which in turn is better than Horace 3. The only unacceptable site from the point of view of seeing is Horace 3.

We have identified the best astronomical sites that meet the goals of the LodeStar Project. From a purely scientific point of view, out of the four sites we have listed, Horace 1 and 2 appear to be the prime sites for the LodeStar Project.

A major finding is that local topography can significantly affect laminar air flows. For the Horace Mesa site, for nominal wind velocities, turbulence can be orographically induced within a few kilometers of the windward edge. Horace Mesa is an ideal interferometry site so long as the instrument is located within a couple of kilometers of the windward edge of the mesa.

Acknowledgments. We wish to thank many people in the Grants area for facilitating access to the sites that we tested. In particular we would like to thank the people of the Acoma Pueblo for their help not only in accessing the site but also for their help in data collection at the Mesa Negra site. We also thank the Guiterrez family for their patience and help in accessing the Horace Mesa sites. We would also like to thank Brenda McBride for providing access across her land on Horace Mesa.

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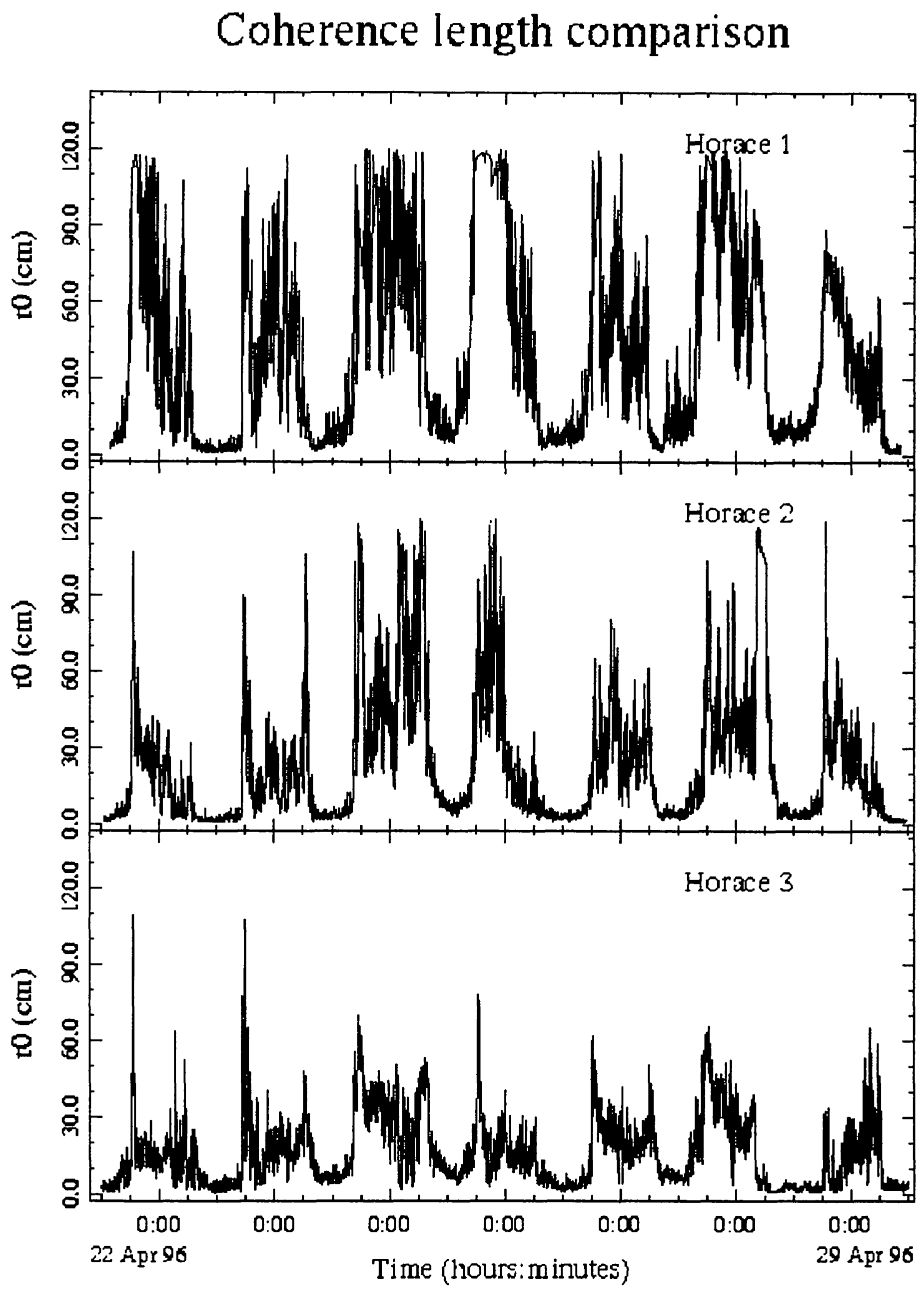

Figure 1. A 2-week record of surface layer coherence lengths.

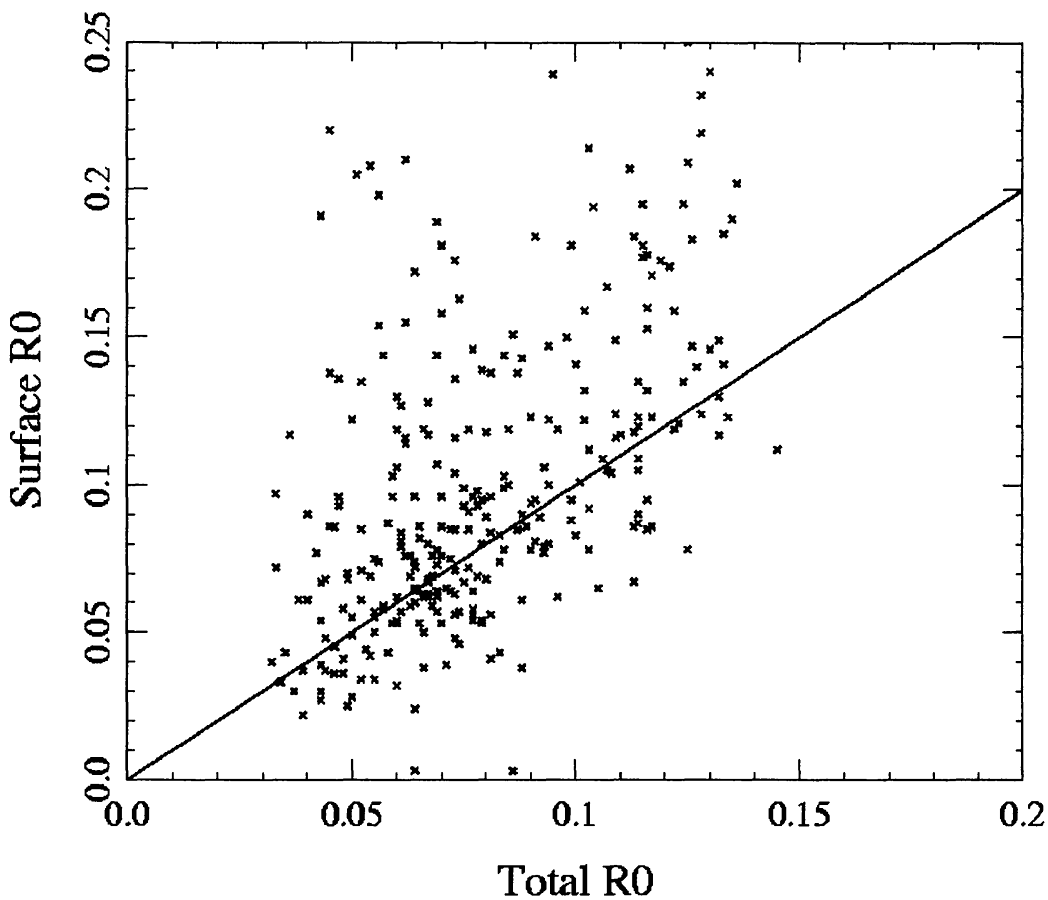

Figure 2. A comparison of the microthermal data and ATMOS data. The r_0's are in meters.

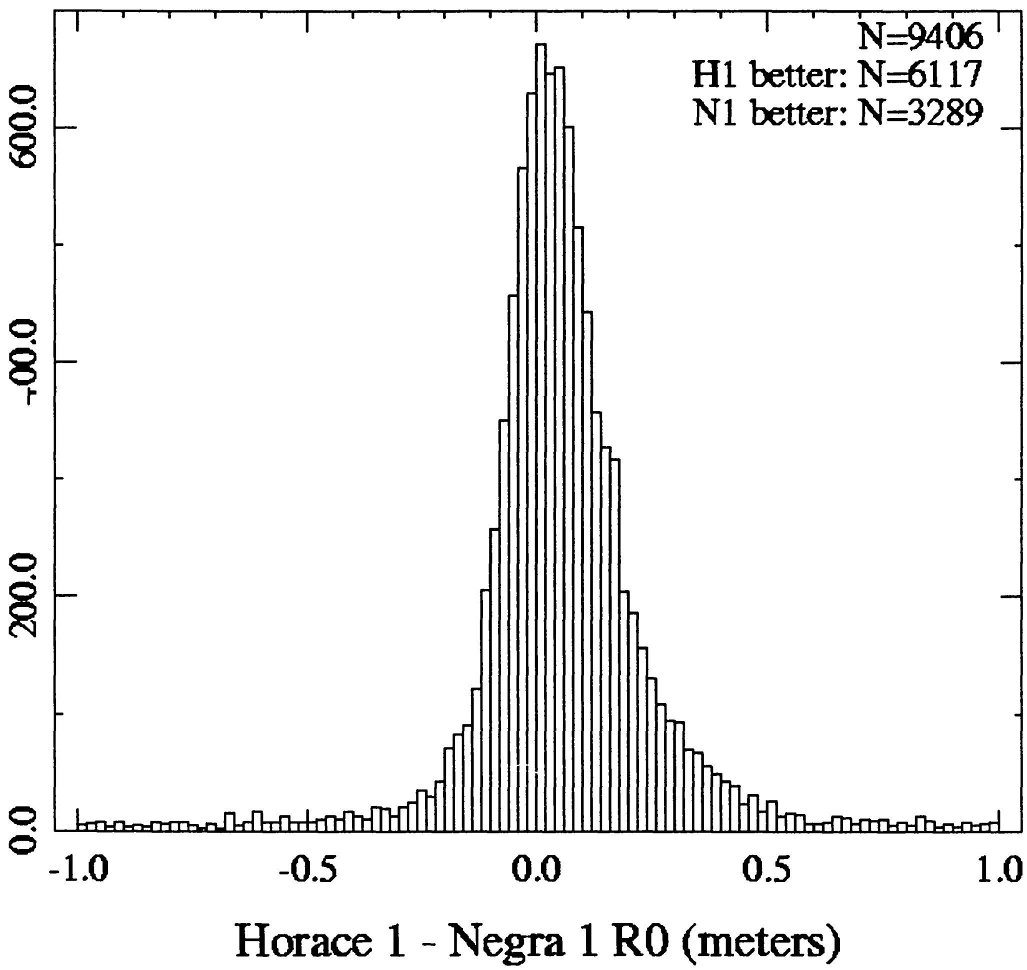

Figure 3. A comparison of r_0 for the Horace 1 and Mesa Negra sites. The comparison is for the months of October and November, 1995.

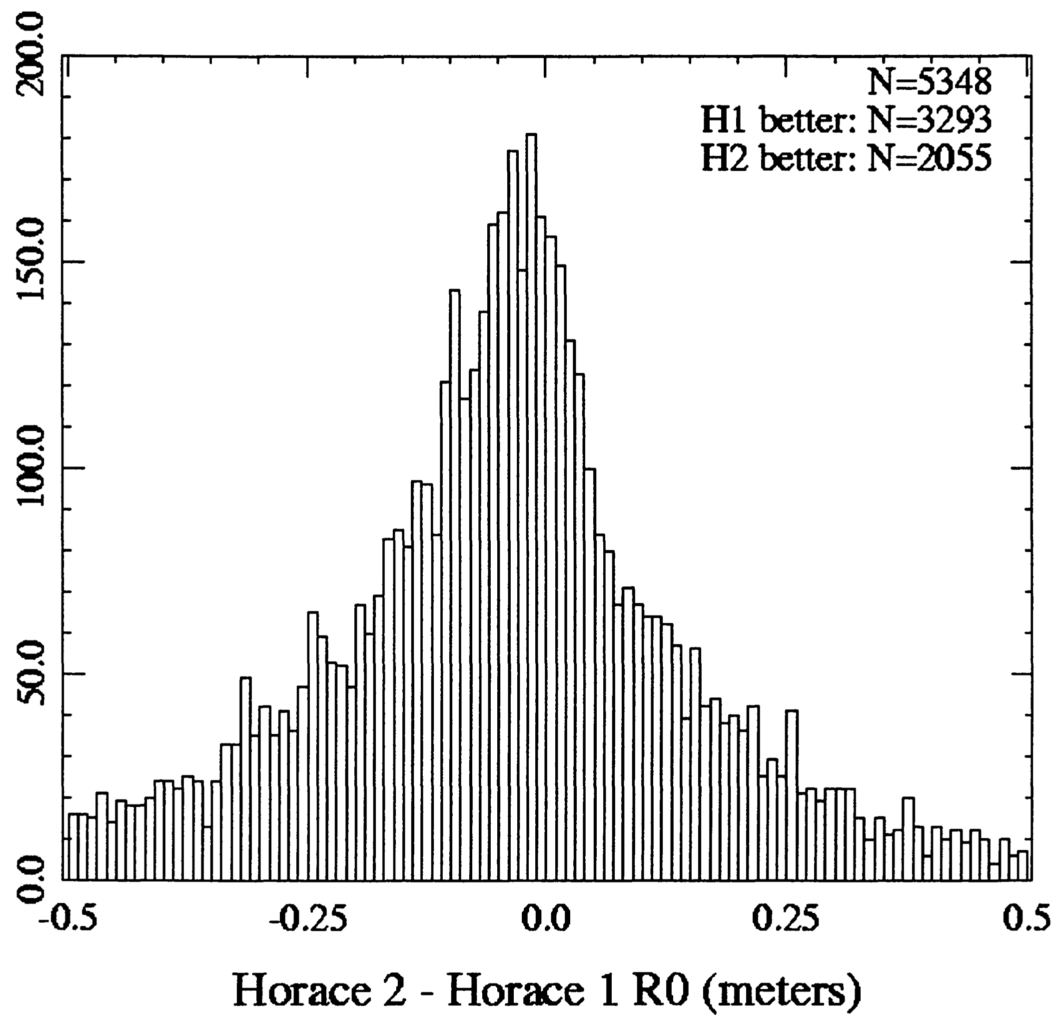

Figure 4. A comparison of the Horace 1 and Horace 2 sites for the months of January through May, 1996.

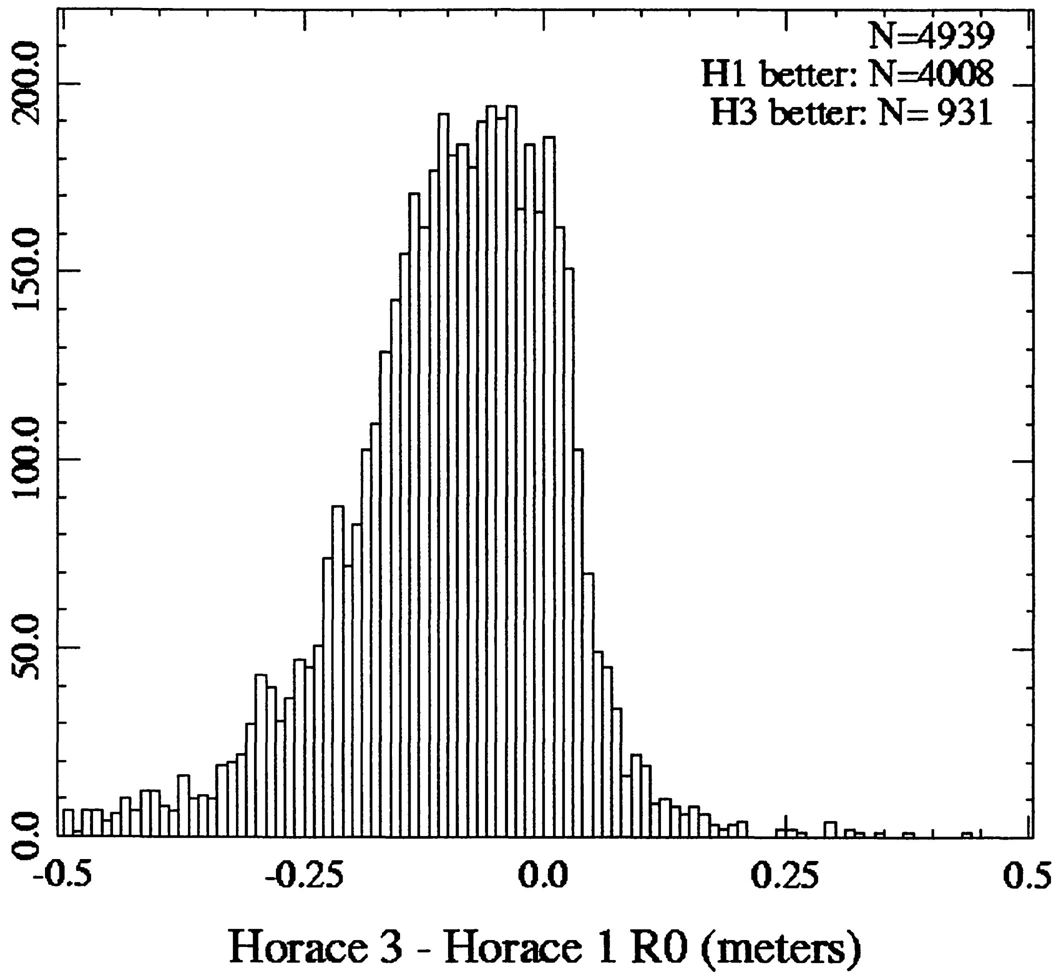

Figure 5. A comparison of the Horace 1 and Horace 3 sites for the months of January through May, 1996.