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# Astronomical Site Monitoring System for the Magdalena Ridge Observatory

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## ABSTRACT

The astronomical site parameters for the Magdalena Ridge Observatory (MRO) are being studied from numerous aspects including meteorological, environmental, seismic and sky quality (e.g. “seeing”, cloud cover). Results to date indicate that MRO is an excellent site for astronomical observing. Seeing measurements of less than 1 arc second in the optical are routinely obtained. Seismic conditions on the mountain ridge are below levels that will cause any major problems for construction and operation of an optical interferometer. Nighttime “allsky” camera imagery indicates a large percentage of clear nights.

**Keywords:** site testing, weather, seismic effects, seeing, MROI, COAST

## 1. INTRODUCTION

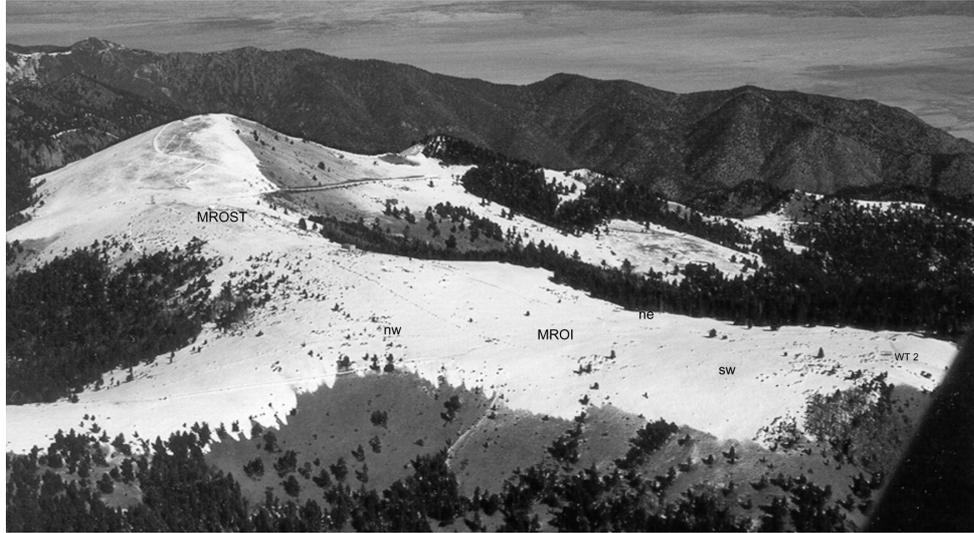
The Astronomical Site Monitoring System for MRO is being developed with two purposes in mind. The first is the collection of long-term historical site conditions that will be used in the design and development of the facility. The second is the real-time and near real-time collection of information (meteorological, environmental and sky quality) that will affect the health and safety of people and equipment, and the quality of astronomical data at MRO. This paper describes the instruments that are currently in place, the data that have been obtained to date, and instruments planned to be installed prior to the operational phase of MRO.

## 2. OBSERVATORY LOCATION

The Magdalena Ridge Observatory (MRO) is located in the Magdalena Mountains 20 miles west of Socorro, New Mexico. The facility will consist of two separate telescope systems: the MRO Single Telescope (MROST) will be a 2.4-meter fast-tracking telescope and the MRO Interferometer (MROI) will consist of 10 1.4-meter telescopes having baselines of up to 400 meters and working in the optical and near-infrared (NIR) (See Creech-Eakman et al. for details<sup>1</sup>). The MROST will be located at the northern end of Magdalena Ridge at an elevation of 10,600 feet (3,230 meters) and the MROI will be located approximately 3,000 feet south at an elevation of 10,450 feet (3,185 meters). Figure 1 is an aerial view of Magdalena Ridge looking northeast from an elevation of approximately 12,000 feet (3650 meters). The locations of the two telescopes are marked as MROST and MROI. The symbols “nw”, “ne” and “sw” indicate the ends of the interferometer arms, while “MROI” is the location of the center of the array. It is worth noting that the site for MRO, sometimes referred to as South Baldy, was considered in the early 1990’s as one of the leading sites for the Millimeter Array.<sup>2</sup>

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**Figure 1.** Aerial view of Magdalena Ridge Observatory. Locations of MROST, MROI and the MROI weather station (WT 2) are indicated. The ends of the interferometer array are indicated by “nw”, “ne”, and “sw”. The MROST weather station (WT 1) is located at the MROST symbol.

### 3. EXISTING INSTRUMENTATION

#### 3.1. Weather stations

Two remotely accessible weather stations are currently in operation at the MRO site. The first has been in operation since June 2000 and is part of the Langmuir Laboratory Meteorological Station, Air Quality Group, New Mexico Tech (NMT) Geophysical Research Center. Dr. Popp, professor of Chemistry, NMT, has allowed us access to his digital data collected there. This weather station consists of a Davis Instruments system that records air temperature, relative humidity, barometric pressure, wind speed, and wind direction. It is located (WT 2 in Figure 1) at the southern end of Magdalena Ridge about 100 feet higher than the MROI.

A second weather station was installed at the MROST site in December 2002. This weather station is a Campbell Scientific Instruments system that measures air and ground temperature, relative humidity, barometric pressure, wind speed, and wind direction.

#### 3.2. “allsky” camera

A Santa Barbara Instruments Group (SBIG) “allsky” camera was installed with remote access in November 2003 at the MROST site. This camera consists of a SBIG ST237 CCD system and an Omnitech Robotics fisheye lens. The fisheye lens has a field of view of  $190^\circ$ . A 60-second optical exposure of the clear moonless night sky shows stars down to at least 7th optical magnitude with the Milky Way clearly visible.

#### 3.3. Seismic stations

For a period of eight months from February through October 2003, four seismic stations were installed at the approximate array arm ends and the center of the planned MROI site. The instruments deployed were three-component broadband Streckeisen STS-2 sensors and data were recorded with the Quanterra Q330 acquisition systems. The complete details of the seismic study can be found in the Masters thesis of R. Alvarado.<sup>3</sup> The units were loaned to us from the Incorporated Research Institutions for Seismology Program for Array Seismic Studies of the Continental Lithosphere Instrument Center in Socorro, New Mexico.

### 3.4. Seeing monitors

Over the course of the last four years “seeing” measurements have been taken at the MRO site using three different Differential Image Motion Monitors (DIMMs). The first was developed by D. Neimeier for his Master’s thesis.<sup>4</sup> This system included a Celestron C-14 telescope with a two-hole aperture plate, where one aperture was covered with a 1.5-arcminute wedge. The CCD camera used to record the data was a DALSA line scan system that was able to read out 128 x 128 8-bit images at about 30 Hz frame rates. Using the method of Sarazin and Roddier,<sup>5</sup> Neimeier was able to compute both longitudinal and transverse estimates of the Fried parameter,<sup>6</sup>  $r_0$ .

A second DIMM system used employed an SBIG STV camera system attached to either a Celestron C-14 or a LX200 12-inch Meade telescope. In this case the aperture plate was a two-hole mask and the telescopes were driven slightly out of focus to separate the two stellar images. The exposures were between 3 and 12 ms. The SBIG software provides a measure of the image separation at approximately 5 Hz frame rate. From this one can compute longitudinal estimates of  $r_0$ .

The third DIMM system, the one that we are currently using, is called DIMMWIT, “Differential Image Motion Monitor Which Is Transportable”. The DIMMWIT was developed by the interferometry group at the Cavendish Laboratory, Cambridge, UK.<sup>7,8</sup> It is capable of being used with either the Celestron C-14 or the Meade 12-inch telescopes that we have available to us. It has three modes of operation with exposure times as short as 1 ms. The first mode, slow 2D, is for measuring  $r_0$ . This mode collects subframes, depending on the subframe size, at a rate of 4 to 6 frames per second. The second mode, fast 1D, collapses a 64 by 64 subframe into a 1 x 64 pixel single line. The frame rate for this mode is 2.25 ms per frame. The third mode, fast 2D, collects a 16 by 8, 4x4 binned sub frame at 3.5 ms per frame. In both fast modes the exposure time is 1 ms. The slow 2D and the fast 2D modes provide estimates of  $r_0$ , in practice calculated in both the longitudinal and transverse directions. The fast 2D mode also provides an estimate of the translations and dispersive wind speeds and the wind direction,<sup>9</sup> which can be used to estimate  $\tau_0$ . The fast 1D mode currently only provides estimates of  $r_0$ .

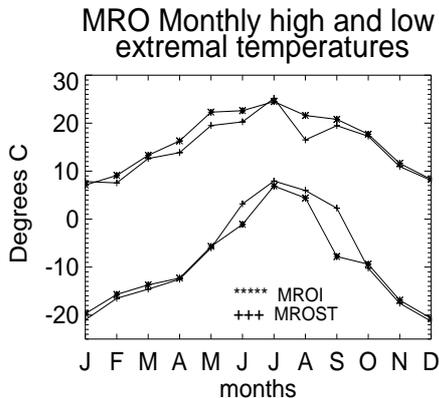
While observations with all of these DIMMs have been made at both the MROST and MROI sites (comprising 24, 22 and 22 nights of data respectively), a decision was made in late 2003 to concentrate on obtaining data with only the DIMMWIT system for characterization of the MRO sites, principally because this is the only system that has a high enough frame rate to allow measurements of  $\tau_0$  as well as  $r_0$ .

## 4. PROPOSED INSTRUMENTATION

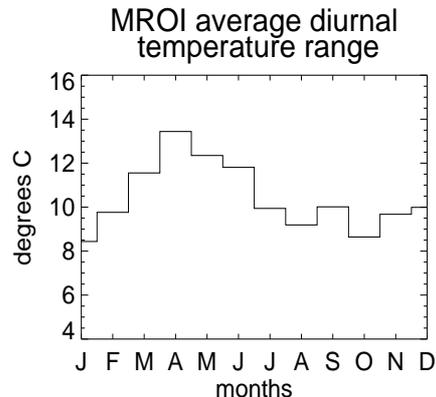
Based on the previously described instrumentation and gathered results over the past four years, we have a fairly good understanding of the long-term meteorological, seismic and astronomical quality of the site. The specific results will be presented below. However, there are several planned instrumentation additions to the site which will help us further access it for astronomical research.

Because we are going to have at least 3 exposed optics at each of the MROI telescopes as well as at the MROST telescope, we have determined that we need to understand the particulate characteristics at the MRO site. These particulates can range from ashes from forest fires, as far away as Arizona and California, to micron-sized airborne particulates. As a result, we are in the process of determining the type of particle counter that will best answer these questions (see Gorgievska<sup>10</sup> from this conference for further details). As part of the particulate assessment, we are also planning to study the long-term degradation effects on optics due to particulates by placing witness samples with the proposed MROI mirror coatings in a small openable enclosure later this year and then monitoring the coating integrity over the next year.

Another aspect of the MRO site we will study before beginning construction of the telescopes is the current state of Radio Frequency Interference (RFI) that exists on the ridge. Measurements made before the construction phase and periodically thereafter will provide a baseline measure of the RFI on the ridge. These measurements take on added importance due to the proximity of the MRO telescope sites to both the Langmuir Laboratory atmospheric research facility and the Very Large Array.



**Figure 2.** Monthly Temperature extremes for both weather stations at MRO.

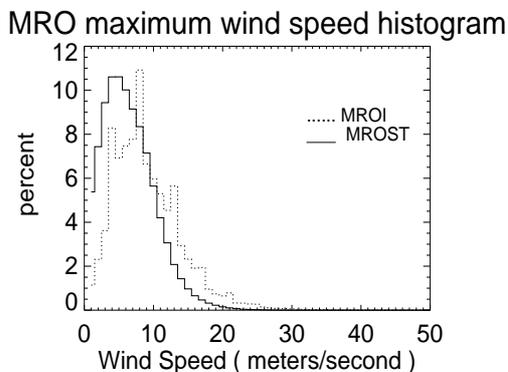


**Figure 3.** Maximum daily temperature range for the MROI (WT 2) weather station over 4 years.

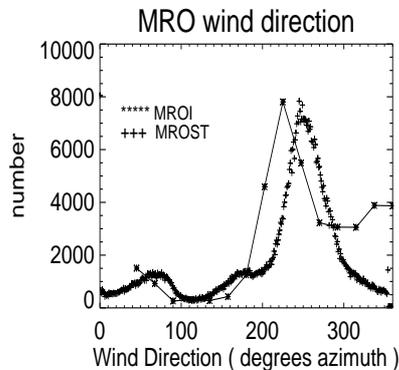
### 5. METEOROLOGICAL RESULTS

The Magdalena Ridge Observatory is located at a high elevation that can produce some fairly extreme weather conditions, typical of these types of mountainous environments. In order to safely construct and operate an astronomical facility at this location we need to quantify the extremes of this environment. With four years of data from weather station 2 (MROI) and 1.5 years of data from weather station 1 (MROST), we are developing a baseline of basic weather data for the site. Figure 2 shows the highest and lowest daily temperatures at both weather stations, recorded monthly. We note that the range in temperatures for any given month does not generally occur within the same 24 hour period. In this time period, the lowest temperature recorded is  $-22^{\circ}\text{C}$  ( $-8^{\circ}\text{F}$ ) and the highest temperature is  $26^{\circ}\text{C}$  ( $79^{\circ}\text{F}$ ). We are also tracking the diurnal temperature variations as this will have an impact on the interferometer building design and stability. Figure 3 shows the average diurnal temperature range that has been recorded by weather station 2, displayed for each month of the year over the past four years. On average, it appears that the day-to-night variation is about  $10^{\circ}\text{C}$  ( $18^{\circ}\text{F}$ ). However, in late winter and early spring the temperature excursion is  $13^{\circ}\text{C}$  ( $23^{\circ}\text{F}$ ).

Finally, we have been tracking wind speed and wind direction, as these quantities will impact telescope and building designs. Figure 4 shows the histogram of wind speeds at the MROST (January 2003 through May 2004) and the MROI (June 2000 through May 2004). These graphs show that the MROI weather station, which is out at the edge of the ridge, records slightly higher wind speeds than the MROST weather station. At the MROI station the wind speed is  $< 13\text{ m/s}$  ( $29\text{ mph}$ ) 85% of the time while at the MROST site the wind speed is  $< 10\text{ m/s}$  ( $23\text{ mph}$ ) 85% of the time. The prevailing wind direction for Magdalena Ridge is shown in Figure 5 which



**Figure 4.** Histograms of MRO wind speeds.



**Figure 5.** Histograms of MRO wind directions show the wind is mainly out of the west.

is a histogram of wind directions (degrees of azimuth, east from north) for both weather stations. There is a highly preferred direction slightly south of west. It should be noted that the winds coming out of the west have traveled over 2200 m (7200 ft) plains with features no higher than 2800 m (9200 ft) for at least 100 km (63 miles) before reaching the MRO location, so there are no local features that cause anomalous turbulence.<sup>2</sup>

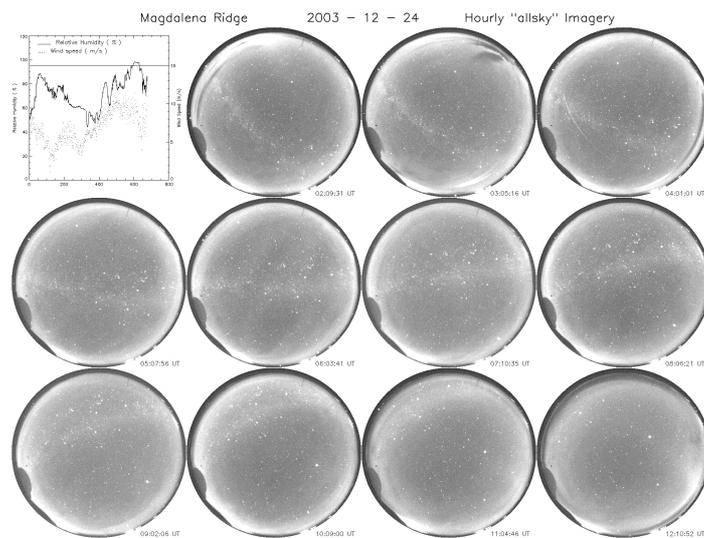
## 6. ALLSKY COVERAGE

Our current procedure for collecting “allsky” imagery is to take a 1-minute exposure approximately every 11 minutes from end-of-evening astronomical twilight until the beginning-of-morning astronomical twilight. This is done whenever the wind speed is less than  $< 15$  m/s (27 MPH) and the relative humidity is  $< 95\%$ . These images are saved for later analysis related to the amount of cloud cover, and from these we generate an hourly mosaic. Figure 6 shows hourly images from a clear moonless night, while Figure 7 shows a moonlit night that started out cloudy and later cleared. The small graph in the upper left hand of Figures 6 and 7 shows the measured wind speed and relative humidity. When either of those graphs is above the solid line, no images are taken.

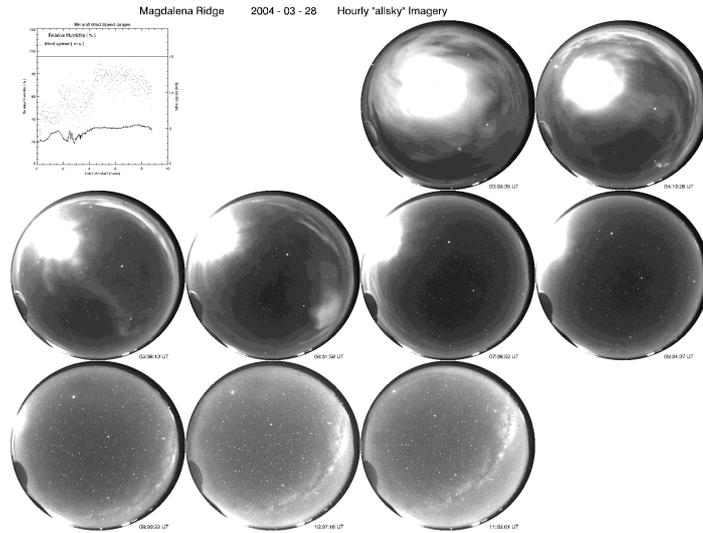
We have collected “allsky” data beginning in November 2003 up through the end of May 2004. During this time period there have been many nights of failed data storage due mainly to the instability of our current power and telnet service at the summit. However, for this time period we do have imagery for 140 nights. Of those 140 nights, the distribution of cloud cover is: 39 nights were completely cloud-covered, 47 nights were clear 25% of the night, 22 nights were clear 50%, 32 nights were clear 75% and 41 nights were completely clear of clouds. Another way to state this is that on 94 out of 140 nights, at least one-third (roughly 3 hours) of each night was clear.

## 7. SEEING MEASUREMENTS

The final sky parameter that we have been measuring is the “seeing”. “Seeing” is a measure of the intrinsic effects of the atmosphere on the incoming stellar wavefronts, and is related to the turbulence of the atmosphere at the site. For MROI, the quantities of interest related to “seeing” are  $r_0$  and  $\tau_0$ , the spatial and temporal time constants of the atmosphere, defined as the size scale or temporal scale over which the atmosphere changes the phase of the incoming wavefronts by one radian. Measurements of the “seeing” have been done with several different DIMM systems since September 2001. The DIMM method used is described in Sarazin and Roddier.<sup>5</sup> We are currently evaluating our “seeing” using the equations of Tokovinin<sup>11</sup> for the conversion from the measured variance of the image separation to values of the Fried parameter,  $r_0$ .<sup>9</sup> The current system, DIMMWIT, has been

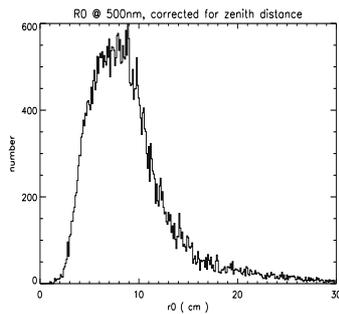


**Figure 6.** Clear night “allsky” mosaic. There is one image per hour. The winter Milky Way is visible.

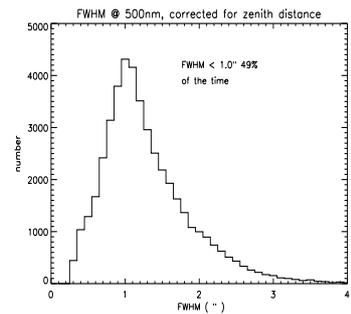


**Figure 7.** Cloudy night allsky mosaic. One can see that the night improved greatly.

developed by O'Donovan and others<sup>8, 12</sup> at the University of Cambridge. It allows for both a low speed method (several frames per second) and two high speed methods (333 or 500 frames per second) of data acquisition (see description above). In a recent “seeing” campaign (May 12 through May 29, 2004), we measured  $r_0$  on 14 nights consisting of 23 hours of data (Figure 8) and obtained a median value of 8.5 cm at 500 nm, corrected for zenith distance. The estimated median wind speeds aloft, calculated from the DIMMWIT data, are 11.6 m/s, leading us to conclude the median timescale for “seeing” is 3.2 ms. During this “seeing” campaign the average ground level wind speeds ranged from 12-15 m/s (27-34 mph). If one converts these values of  $r_0$  to full width half maxima (FWHM) “seeing” values, the median value of the gaussian FWHM is 1.0 arcseconds. This is typically considered “good seeing”, which we obtained for 49% of the data taken. Figure 9 shows the corresponding histogram of the FWHM.



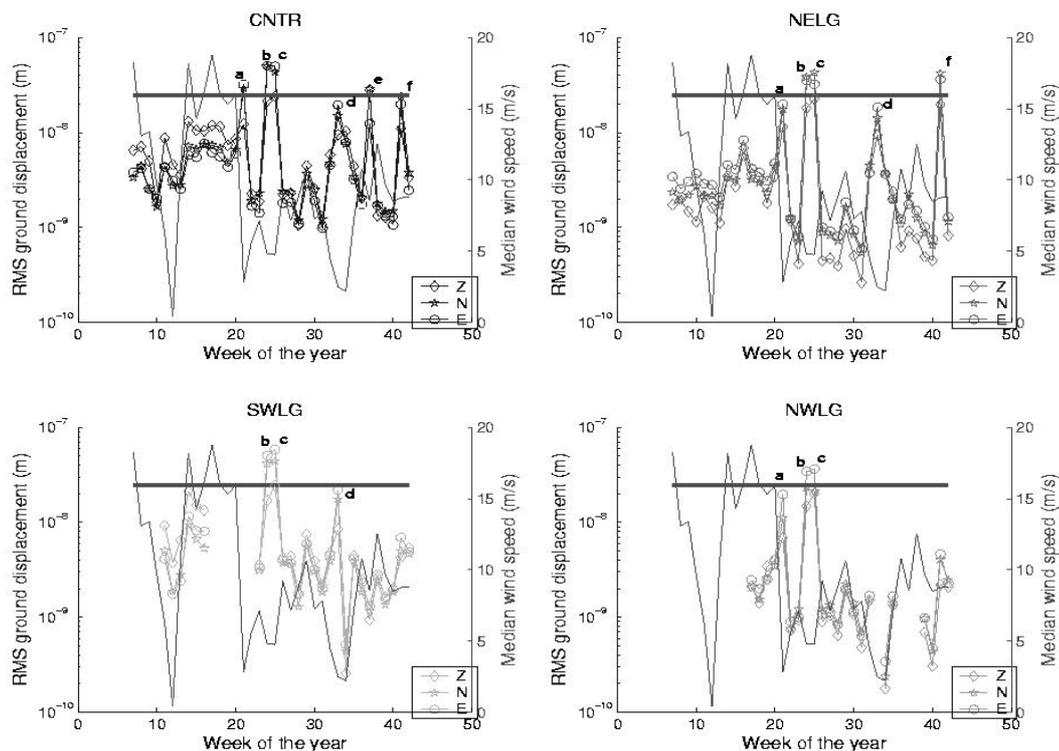
**Figure 8.** Histogram of  $r_0$  at 500 nm for 5/12/04 through 5/29/04. The median value of  $r_0$  is 8.5cm. The histogram comprises about 23 hours of data total and was binned in 0.1 cm increments.



**Figure 9.** Histogram of FWHM at 500 nm for 5/12/04 through 5/29/04. The median value of FWHM is 1.0” which we obtained 49% of the time. The binning is 0.1 arcseconds.

## 8. SEISMIC STUDY

Ground vibrations, whether man-made or naturally-induced, can potentially introduce unacceptable phase jitter in an interferometer, so it is important to characterize the seismic environment of the MROI site. With this in mind, a set of four seismic measuring stations was set at the proposed site of the MROI array, one station in the



**Figure 10.** Seismic measurements from Magdalena Ridge. The four graphs show the largest-amplitude seismic events measured at each of the four seismic stations situated on the MROI array arms. The events labeled “a” through “f” are identified with specific natural and man-made transient events as explained in the text. The bold horizontal line indicates the maximum acceptable vibration level for the interferometer (25 nm rms). Wind speed is also shown (solid line) to indicate possible noise from tree wind shake.

middle of the array and one at the end of each arm. These stations were operated almost continuously over the period February to October, 2003.

Our study concentrated on vibrations at frequencies greater than 1 Hz, since lower-frequency vibrations are unlikely to affect an interferometer which has a basic integration time of a few milliseconds. The criterion adopted for “acceptable” levels of vibration was that the rms vibration should be less than 25 nm, i.e.  $\lambda/20$  at 500 nm. Initial results indicated that the site was almost always much quieter than this level, so our study then focused on determining the frequency and character of extreme events. To this end, the noisiest period in each week was identified, and the vibration level at these times is shown in Figure 10.

As can be seen from the figure, on only a handful of occasions during the entire 36-week period was the noise level above the acceptable upper bounds for the interferometer. A number of identifiable transient phenomena are labeled a-f in these figures. Events “a” and “b” were caused by small local earthquakes, “c” by an earthquake with an epicenter in the Amazon, “d” is a regional earthquake, and “e” and “f” were caused by MRO pickup trucks driving past the seismometers. Other possible noise sources such as the switching on of a 150kW electrical generator 600 meters from the array, or wind shaking of trees near the array, did not cause enough vibration to make it into this “high-noise event” table.

Overall, it appears that the Magdalena Ridge presents a benign seismic environment for interferometric operation. Careful design of the array so that it does not introduce significant new noise sources or resonantly amplify the natural vibrations should be all that will be required - elaborate isolation schemes do not appear to be necessary.

**Table 1.** Summary of investigated site conditions for MRO

Condition	value	fraction of night times
Wind speed MROI	<13 m/s	85%
Wind speed MROST	<10 m/s	85%
Useable nights	94 out of 140	67%
Seismic activity	<4nm rms	83%
Prelim. Seeing	<1.0"	49%

## 9. CONCLUSIONS

The astronomical site monitoring done so far has shown that Magdalena Ridge is an excellent site for the construction and operation of the Magdalena Ridge Observatory. For the most recent DIMM campaign, 49% of the “seeing” measurements gave values better than 1.0 arcseconds. This campaign was conducted in May of this year during the windy season (when winds were averaging 12 - 15 m/s (27 - 34 mph)) and shows a median  $r_0$  of 8.5 cm at 500 nm and median  $\tau_0$  of 3.2ms. The “allsky” camera’s first half year of operation has shown that MRO has at least 67% of its nights with more than 3 clear hours each night. The MRO site is quiet in seismic background noise for a continental interior site and is overall a benign location for building and operating the proposed interferometer. The wind is high but not out of bounds relative to the design specifications of either the MROI or the MROST. Finally, the temperature extrema will not present any construction or operational limitations for the observatories. All in all, the conditions on Magdalena Ridge are very good and will allow us to build a world-class observatory at this site.

## 10. ACKNOWLEDGEMENTS

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