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GMT SITE EVALUATION AT LAS CAMPANAS OBSERVATORY

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RESUMEN

El proyecto del Gran Telescopio Magallanes se encuentra en la afortunada situación de tener acceso a un sitio ya desarrollado y con una larga historia de excelente desempeño. El Observatorio de Las Campanas tiene cielos oscuros, poco o ningún riesgo de contaminación lumínica en el futuro, *seeing* excelente, vientos moderados y una gran fracción de noches despejadas. Nuestro esfuerzo en la evaluación de sitios se concentra en identificar el mejor lugar, dentro del Observatorio de las Campanas, en términos del *seeing*, perfil de turbulencia y velocidades del viento, así como cuantificar, dentro de las metas científicas del mediano infrarrojo para el GMT, el potencial impacto del vapor de agua precipitable en términos tanto de precisión como de variabilidad temporal. Por lo tanto, estamos midiendo características metereológicas (presión, temperatura, humedad, viento y cubrimiento de nubes), *seeing*, perfil de turbulencia de la atmósfera libre (arriba de 500 m), vapor de agua precipitable, y contaminación lumínica en cuatro sitios dentro de área del LCO.

ABSTRACT

The Giant Magellan Telescope project is in the fortunate position of having clear access to a developed site with a long history of excellent performance. Las Campanas Observatory has dark skies, little or no risk of future light pollution, excellent seeing, moderate winds and a high fraction of clear nights. Our site testing effort is concentrated on identifying the best peak within LCO in terms of seeing, turbulence profile, and wind speeds and on quantifying the potential impact of precipitable water vapor on GMT mid-infrared science goals by characterization in terms of both precision and time variability. Thus, we are measuring meteorological characteristics (pressure, temperature, humidity, wind, and cloud cover), seeing, the turbulence profile of the free atmosphere (above 500 m), precipitable water vapor, and light pollution at four sites within the LCO property.

Key Words: **SITE TESTING**

1. INTRODUCTION

The Giant Magellan Telescope (GMT) Science Working Group determined that Las Campanas Observatory (LCO) has the potential to meet its science goals. The GMT project is in the fortunate position of having clear access to a developed site with a long history of excellent performance. The seeing quality is as good or better than other developed sites in Chile, light pollution is negligible and likely to remain so for decades to come, and the weather pattern has been stable for more than 30 years. Our site testing effort is, therefore, concentrated on identifying the best peak within LCO in terms of seeing, turbulence profile, and wind speeds. Additionally, quantifying the potential impact of precipitable water vapor on GMT mid-infrared science goals requires further characterization in terms of both precision and time variability. In preparation for a report to be assembled in mid-2008 that will form the basis for the site selection, this paper describes our ongoing site testing efforts in the context of known properties based on the history of almost 40 years of operations at the site.

2. SUMMARY OF KNOWN SITE CHARACTERISTICS

The Carnegie Institution of Washington established LCO in 1969 to build the Swope 1-m telescope in 1971 and the du Pont 2.5-m telescope in 1977. The purchase of the land was arranged by Horace Babcock, then the Observatory's director. The property (see Figure 1) is approximately 200 km^2 and located just north of the European Southern Observatory's La Silla. LCO became the Observatories primary observing site in 1986 with the transfer of Mt. Wilson, in Southern California, to the Mount Wilson Institute. The twin Magellan 6.5-m telescopes, completed in 2001, are operated by Carnegie for the Magellan consortium including Harvard, MIT, and the Universities of Arizona and Michigan in addition to Cargnegie. Also located at LCO but not operated by Carnegie are the 1.3-m Warsaw telescope

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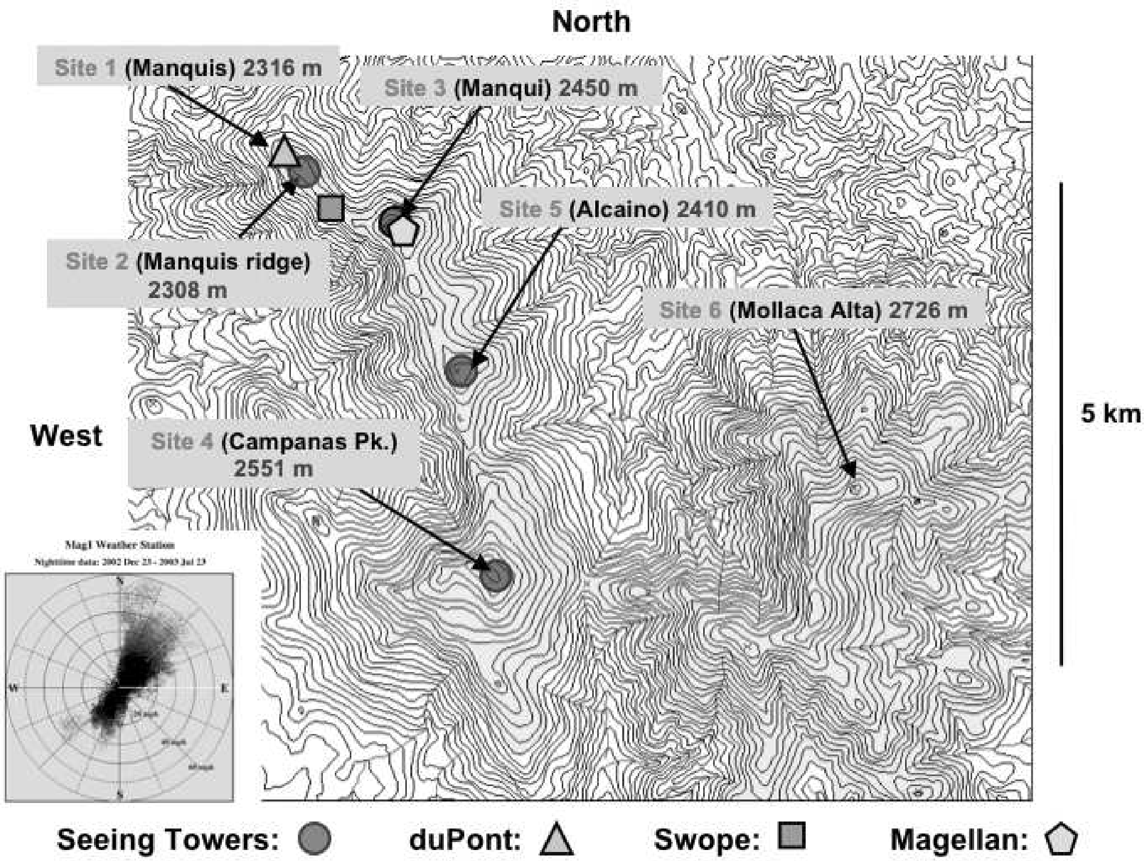

Fig. 1. Topographic map showing the peaks within the LCO property including some current facilities and potential GMT sites. The circles show the locations of site testing towers. The sites of the du Pont, Swope, and Magellan telescopes are also indicated. The wind rose for Manqui is plotted at lower-left showing the prevailing wind directions (∼80% from the NE and ∼20% from the SW).

and a NASA Telescopes in Education remotely operated 35-cm telescope. Given the long operational baseline, a fair amount was known about the LCO site when the current GMT site testing effort began. What follows is a summary of that information. Many more details can be found in the GMT CODR (2006).

The study of world levels of artificial sky brightness by Cinzanto et al. (2001) based on Satellite imagery obtained in 1996-1997 shows that LCO is located outside any regions of increased brightness. Strong light pollution laws implemented by the Chilean Government in 1998 and small population growth in the nearest towns suggests that light pollution will remain negligible in the future (GMT CODR 2006).

The fraction of photometric and otherwise usable nights at LCO can be assessed from a number of sources including, the Swope, duPont, and Magellan telescope logs (from which there is no obvious long term trend in the fraction of usable nights apparent in the almost 40-year history of LCO), the Global Oscillations Network Group Site survey (Hill et al. 1994), nearby La Silla Observatory cloud cover statistics[2], and remote sensing studies like those of Erasmus & van Staden (e.g. 2003). The results from these widely varying and independent sources are generally consistent and indicate that the average photometric fraction is 60–65%, with ∼85% of the potential observing time useful (GMT CODR 2006).

Throughout the LCO property, median seeing values range from $0\farcs6$–$0\farcs7$. The Magellan Telescopes Site Survey (Persson, Babcock, & Irwin 1987; Persson, Carr, & Jacobs 1990) tested three sites at LCO (Manquis Ridge, Manqui, and Campanas Peak). The seeing at Manquis Ridge was found to be slightly worse ($0\farcs05 \pm 0\farcs02$) than that at Manqui, the site of the current Magellan telescopes. The seeing at Campanas Peak was inferred, based on a smaller

[2]http://www.eso.org/gen-fac/pubs/astclim/lasilla/

data set, to be similar to that at Manqui. Image quality of the Magellan Clay 6.5-m telescope as measured from guide camera images indicates that the seeing at Manqui has not changed significantly since the Magellan Site Testing measurements made 18 years ago (GMT CODR 2006). Furthermore, Magellan guide camera seeing measurements indicate a seasonal variation such that the mean seeing during the Southern summer is approximately $0\farcs1$ better than the mean during the winter.

The meteorological measurements made during the Magellan Telescopes Site Survey included wind speed and direction and temperature. The wind direction at all three sites is highly bimodal (~80% of the time from NE and ~20% from SW). There is a wind speed trend with altitude such that Las Campanas Peak is the windiest site resulting in 2–3% of otherwise useable observing time with wind speeds in excess of the current Magellan limit of 35 mph whereas this is 1% at Manqui, the Magellan Telescopes location.

Historical measurements of precipitable water vapor are essentially non-existent. Useful information, however, can be gleaned from modest amounts of data that exist for the nearby observatories of La Silla, Tololo, and Pachon. During the VLT site survey (1983–89) at La Silla, measurements were made using a mid-IR sky radiance monitor where the absolute scale of PWV was determined via simultaneous coudé spectroscopy of a water vapor line at 694.38 nm (Morse & Gillette 1982). They found that the summertime PWV median is ~ 6 mm and in winter it is ~ 2 mm. Also, the first quartile in winter is ~ 1.5 mm.

3. SITE EVALUATION PROGRAM

An extensive site testing program has been underway for approximately two years to identify the best available location within the LCO property for the GMT. We are measuring meteorological characteristics (pressure, temperature, humidity, wind, and cloud cover), seeing, the turbulence profile of the free atmosphere (above 500 m), precipitable water vapor, and light pollution at four sites within the LCO property (see Figure 1). A description of the sites and the instruments in use follows as well as some preliminary results.

Cerro Manqui is home to the Magellan telescopes. Although there is not sufficient space to add another large telescope, it is the best characterized site at LCO and therefore it serves as a reference. The Manquis Ridge site, between the du Pont and Swope telescopes, is the lowest altitude site. The Magellan site survey found it to have slightly poorer seeing than Manqui but also lower wind speeds. Las Campanas Peak is the highest of our sites and was found by the Magellan site survey to have seeing similar to Manqui but significantly higher wind speeds. Finally Alcaino, in between Las Campanas Peak and Manqui but lower than both, was the site of the Nagoya 5-m radio telescope until 2004. It was not included in the Magellan site survey and the current studies provide the first detailed examination of its properties. There are no current plans to test the currently undeveloped La Mollaca Alta, to the East of the main ridge.

Cloud cover and light pollution are being monitored through the use of the Campanas All-Sky Camera (CASCA) which was provided by CTIO as a copy of the Tololo All-Sky Camera (TASCA). It is installed near the Swope telescope and takes images of the entire sky in four standard broadband filters (B, R, Z, and Y) regularly throughout the night. Sodium filter images are taken twice nightly to monitor light pollution. Software under development by the LSST project will eventually be available for analyzing the CASCA images to give quantitative, real-time information on the sky transparency. Visual estimates of cloud cover are also recorded by the site testing operators several times a night.

Other meteorological data are being collected using weather stations manufactured by Davis Instruments Corp and mounted on 10-m towers. A Weather Monitor II station was used on Manqui between 2000 and 2005. Two newer models (Vantage Pro and Vantage Pro2) which utilize the same basic sensor technology to measure temperature, humidity, atmospheric pressure, and wind speed and direction have been in use since 2005 at all four sites. Preliminary studies (summarized from the GMT CODR 2006) of the new data collected confirm highly bimodal nature of wind direction as found by the Magellan site survey. Futhermore, the SW component is stronger in Southern summer than in winter, and also stronger during the first half of the night. We have also confirmed that Las Campanas Peak is windier than Manqui and discovered that Alcaino has wind speed characteristics very similar to Manqui which is not surprising given their similar altitudes. Furthermore, humidity statistics show a strong seasonal variation whereby, the winter months are the driest, consistent with that seen at nearby La Silla in the VLT site survey (Morse & Gillette 1982).

The seeing is being monitored at each of the four sites through the use of differential image motion monitors (DIMM) in 7-m towers. The DIMM, first implemented in a modern fashion by Sarazin & Roddier (1990), functions by relating the FWHM from a long exposure in a large telescope to variances in the difference in the motion of two images of the same star through the use of Kolmogorov turbulence theory. The two images are created by placing a mask with two sub-apertures containing prisms at the front of the optical tube. The GMT instruments, using commercially available equipment like Meade telescopes and SBIG CCD cameras, are based on the CTIO RoboDIMM[3] but have several improvements. Image quality has been improved by using two, thinner prisms as opposed to one thicker prism and an open aperture. Following a technique developed by the TMT project, the CDIMM (Carnegie DIMM[4]) software uses a drift scan readout mode which allows for many more image motion measurements to be made per minute and thus improved statistics.

Christoph Birk a programmer at Carnegie was responsible for developing our new code. It can work in two different data acquisition modes (one each for the ST5 sub-raster image mode and ST7 continuous readout mode) and is easily changed between the two. It can control both the Meade LX200 and RCX400 telescope and features a star catalog and sky map. It controls both the telescope motion and the focus. A spiral search pattern allows the operation to be almost automatic. Additionally it can also control the MASS Turbina control program and thus act as its supervisor.

Turbulence in the atmosphere above 500 m is being monitored by a multi-aperture scintillation sensor, MASS, (Kornilov et al. 2002). The spatial scale of the scintillation variation depends on the distance to the layer in which the turbulence giving rise to the wave front phase disturbance exists. Thus, the turbulence profile at a small number of discrete layers can be restored by fitting a model to the differences between the scintillation indices within four concentric apertures. The GMT MASS has an accompanying DIMM built into it. Instead of having prisms in a mask at the end of the optical tube, the two images are created by small mirrors in the pupil plane of the MASS instrument. This instrument, known as a MASS/DIMM, was fabricated and provided by CTIO[5] and put into operation in a tower at the Magellan telescopes site (Manqui). Since the MASS operates only above 500 m , the profiles are valid for all nearby sites. In addition to the turbulence profile, the MASS also measures free atmospheric seeing (essentially the integral of the turbulence profile), the adaptive optics time constant and the isoplanatic angle due to the free atmosphere. The difference between the total DIMM turbulent integral and the free atmosphere MASS turbulent integral is a measure of the portion of the total seeing contributed by a ground layer.

A database[6] is under development to aid in the analysis and presentation of this extensive data set.

3.1. *Preliminary seeing and turbulence statistics*

Between April 2005 and December 2006 we collected approximately 300 nights of DIMM seeing measurements at Manquis Ridge, Manqui, and Alcaino. The ∼50% efficiency during this 20 month period is artificially low given that during the first six months of this period we were commissioning instruments and did not have operators working all shifts. Las Campanas Peak became operational in September 2005 and in its first 15 month stint has an efficiency of ∼65%. This is quite good assuming a usable fraction of ∼85% and considering that equipment failures are bound to happen when using equipment designed for amateur use.

The DIMM located at the Magellan Telescopes site, Manqui, is a combined MASS/DIMM instrument. In an early, side-by-side comparison between the MASS/DIMM and one of the GMT DIMM units, an average offset of 0.″08 was observed where the MASS/DIMM measured systematically smaller seeing. This offset was determined during a period of approximately one month and seen to vary between 0.0″and 0.″1. Further study of this issue resolved this difference as being due to incorrect placement of the CCD (in terms of distance from the focal plane) on the MASS/DIMM. MASS/DIMM seeing measurements taken before this equipment correction are adjusted upwards by 0.″08.

The DIMM measurements have been filtered to remove poor quality data due to four possible criteria: focus, read noise, low flux, and number of measurements during one minute. We measure focus using the mean separation of the two images throughout a minute of measurements. Nominal focus is determined on a night with good seeing by varying the focus and maximizing the Strehl ratio. The CDIMM software is designed to keep the mean separation within a range of 1 pixel on either side of the nominal focus. There are, however, some measure-

[3] `http://www.ctio.noao.edu/telescopes/dimm/dimm.html`

[4] `http://www.ociw.edu/~birk/CDIMM/`

[5] `http://www.ctio.noao.edu/~atokovin/profiler/`

[6] Along with other GMT site testing information, it can be found at: `http://www.lco.cl/lco/operations-inf/gmt-site-testing-1`

TABLE 1

SEEING AT FOUR SITES

Location	Dates	Number of Nights	Seeing 25% ($''$)	Seeing 50% ($''$)	Seeing 75% ($''$)
Manquis Ridge	Apr 05 - Dec 06	314	0.55	0.68	0.86
Cerro Manqui	Apr 05 - Dec 06	318	0.53	0.65	0.83
Cerro Alcaino	Apr 05 - Dec 06	290	0.50	0.63	0.80
Las Campanas Peak	Sep 05 - Dec 06	288	0.52	0.63	0.78

ments throughout the night but especially at the beginning of the night that need to be removed because the separation is outside the nominal range. Additionally the MASS/DIMM does not have automatic focus control as there is not space for a micro-focus controller between the instrument and the telescope mount. The operators monitor the focus and adjust it as needed but naturally this leads to a higher percentage of MASS/DIMM measurements taken out of focus that need to be removed. The filters for flux, read noise, and the number of measurements allow for the removal of suspect quality data due to clouds or tracking errors.

Table 1 shows preliminary seeing statistics for the four sites. The reader should bear in mind that the analysis presented in this section is still very preliminary, and that a full determination of the errors in the DIMM measurements has yet to be carried out. Furthermore, comparing only measurements taken concurrently at each site would increase our confidence in the results. Regardless of the limitations of these results, it is encouraging that they seem to be in overall agreement with previous studies. It appears that both Alcaino and Las Campanas Peak have seeing qualities that are very similar to Manqui and possibly even better. The as yet uncharacterized Alcaino site is therefore a very promising site given its lower wind speeds and good seeing.

Analysis of the MASS portion of the MASS/DIMM data is ongoing. Preliminary results are presented for the first complete year's worth of data. This data has been reprocessed using a new version of Turbina (Kornilov & Shatsky 2005) to correct for the effect of strong scintillation under poor seeing conditions (Tokovinin 2006). Strong scintillation affects the turbulence profile and free atmosphere seeing by over-estimating turbulence and spreading turbulence to lower levels.

During our first year of operation we obtained 244 nights of MASS/DIMM data. As mentioned above, instrument testing was ongoing in the early part of this year. The seeing contribution by the ground layer (defined here as lower than 500 m) is calculated at each matching time by converting seeing from each of the DIMM and MASS into turbulence integrals and then subtracting. The resulting turbulent integral is then converted back to seeing. In median conditions, the ground layer at Manqui contributes ~40-50% of the total turbulence integral. Table 2 shows the quartiles for the cumulative seeing histograms for each of the MASS, DIMM, and ground layer. Also shown is the AO time constant due only to the free atmosphere.

Again the reader is cautioned that these are preliminary figures and the error estimates are not yet well determined. For example, the spectral response of the instrument has not yet been confirmed. Weighting functions used to restore turbulence profiles are wavelength dependent and therefore depend on the spectral distribution of both the stellar targets spectrum and the response of the MASS system (Tokovinin 2003). Uncertainties in the effective spectral response cause systematic errors in the profile restoration (Kornilov 2006).

These data were used in a comparison to Ground Layer Adaptive Optics experiments at Magellan (Athey et al. 2006). The MASS/DIMM ground layer detection was found to be correlated (but not one to one) with that detected by the GLAO. On the best nights, an RMS image size reduction of 30% over a $7'$ separation in the V-band was achievable, whereas that on a typical night was only a 10% reduction.

3.2. *PWV measurements and calibration*

An important objective of the GMT site evaluation is to characterize the column of precipitable water vapor found over the LCO site. Given its importance, our lack of previous information, and short time-frame, we elected to approach the problem with the redundancy of four different instruments. While none of the instruments is ideal to answer our questions alone, together they have that potential. Each system is described briefly below, followed by a summary of first results and our efforts to absolutely calibrate them.

TABLE 2

QUARTILES OF THE SEEING AND AO TIME CONSTANT CUMULATIVE HISTOGRAMS FROM MASS/DIMM ON CERRO MANQUI, APRIL 2005 - APRIL 2006

	25%	50%	75%
DIMM total seeing ($''$)	0.54	0.66	0.83
MASS free atmosphere seeing ($''$)	0.33	0.44	0.59
ground layer seeing ($''$)	0.30	0.40	0.52
free atmosphere AO time constant (ms)	1.52	2.55	3.39

A GPS system has been installed by a group from Ohio State University led by Michael Bevis. The precision of PWV measurements made with GPS systems is low (typically in the 0.5-1 mm range) and below about 2 mm of PWV they are insensitive. Nevertheless, these devices have the advantage of being inexpensive and easy to operate[7].

A copy of IRMA (Infrared Radiometer for Millimeter Astronomy[8] has been purchased from the University of Lethbridge Astronomical Instrumentation Group. IRMA monitors a spectral emission line of water vapor at a wavelength of $\sim 20\,\mu$m. The advantage of working at this wavelength is that the water lines are very strong and uncontaminated allowing good signal-to-noise measurements to be achieved on very short time scales. IRMA has also been adopted by the TMT project for measuring PWV, and GMT is collaborating with TMT to produce the copies of IRMA that will be used by both projects to monitor the PWV at LCO and several sites in the north of Chile. While our unit is fabricated, an older copy of IRMA that is currently under refurbishment and will hopefully be ready to collect data during the Southern winter of 2007.

A 225 GHz tipping radiometer (Tipper) belonging to the Arizona Radio Observatory was loaned to LCO during the Southern winter months of 2005. This instrument measures the opacity due to the wing of a strong water vapor absorption line at 183 GHz. The resulting opacity at 1.2 mm can be directly related through calibration to the PWV.

Absolute calibration is achieved through High-dispersion spectroscopy of certain weak H_2O absorption lines in the optical and near-IR wavelength regions. Swings et al. (1990) combined high resolution echelle spectroscopy of a water vapor line at 694.38 nm with a technique devised by Brault, Fender, & Hall (1975) to calibrate mid-infrared sky radiance measurements obtained at the La Silla Observatory during the VLT site survey. Fractional populations in energy levels corresponding to wavelengths between 590-730 nm are temperature insensitive over temperatures found in Earth's atmosphere. This allows a robust measurement of PWV without a detailed model atmosphere as long as the lines are unsaturated.

We have extended this method with improved partition functions and additional lines. Rapidly rotating A and B type stars with magnitudes between 4 and 6 are readily observed with the MIKE echelle spectrograph on the Magellan Clay telescope. This method is not practical for constant monitoring of the PWV, but provides an excellent tool for verifying the absolute calibration of the other methods.

An excellent correlation is obtained between MIKE PWV measurements and 225 GHz Tipper opacities. The calibrated tipper PWV data for 29 clear nights in Southern winter 2005 give a median of 2.8 ± 0.3 mm, in agreement with VLT Site Testing measurements at La Silla. Furthermore, in the Southern hemisphere winter months, we can expect good conditions for infrared observing ($\lesssim 1.5$ mm) at the tenth percentile level. Further details of both the calibration method and the results from the 2005 Tipper campaign can be found in Thomas-Osip et al. (2007).

4. FUTURE WORK

Much work remains to be done in providing a final analysis of this extensive and growing data set. Database improvements will soon allow many types of analysis that we have not yet had time to complete like clear night weather statistics, useable wind speed seeing statistics and correlations between seeing and meteorological parameters. Statistics of the turbulence profiles will be used as inputs to AO modeling for the design of GMT instruments. Exploration of the ground-layer turbulence (in the first

[7] http://www.paroscientific.com/GPSMETSupport.htm

[8] http://research.uleth.ca/irma/

500 m) will begin in the later half of 2007 using LuSci (Tokovinin 2007) and SLODAR (Lambert, Jenkins, & Goodwin 2006). Further PWV characterization is expected with the arrival of IRMA. And the analysis of CASCA images and operator cloud logs may allow for real-time transparency determinations.

Comparisons of our new data with historical data going back over the almost 40 years of operations at LCO will provide insight into the long term stability of the site. Monitoring of meteorological conditions (including cloud cover), seeing, the turbulence profile, and PWV at the final selected site is envisioned to continue for the lifetime of the GMT project as such data will be extremely valuable in evaluating and optimizing the performance of the telescope, and for maximizing the eventual science return.

5. CONCLUSIONS

The long history of excellent conditions at LCO, concerns regarding biases in short-term site surveys, and limited resources led the GMT project to focus its site evaluation activities to certain peaks within the LCO property. LCO has dark skies, little or no risk of future light pollution, excellent seeing, moderate winds and a high fraction of clear nights. The primary downside of LCO, and any moderate elevation site in Chile, is its mediocre mid-IR performance much of the year. For this reason, we have focused on characterizing the precipitable water vapor, especially in the winter months when it is lowest, to allow for a final determination of how long it would take to complete the mid-IR science goals. Finally, the site evaluation at LCO to be completed in 2008 will take into account seeing (both image quality and stability), wind speeds, and ground layer characteristics.

We are grateful to to CTIO and the TMT and LSST projects for providing equipment and valuable assistance. We greatly appreciate the loan of the Tipper by ARO. Furthermore we are indebted to the many Magellan observers who have participated in our efforts to absolutely calibrate the precipitable water vapor scale at LCO. We are also grateful for many useful discussions with M. Johns, P. McCarthy, M. Phillips, S. Shectman, M. Schoeck, and A. Tokovinin.

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