A Direct Measurement of Atmospheric Dispersion in $N$-band Spectra: Implications for Mid-IR Systems on ELTs

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ABSTRACT. Adaptive optics will almost completely remove the effects of atmospheric turbulence at 10 $\mu$m on the Extremely Large Telescope (ELT) generation of telescopes. In this article, we observationally confirm that the next most important limitation to image quality is atmospheric dispersion, rather than telescope diffraction. By using the 6.5 m MMT with its unique mid-IR adaptive optics system, we measure atmospheric dispersion in the $N$ band with the newly commissioned spectroscopic mode on MIRAC4-BLINC. Our results indicate that atmospheric dispersion is generally linear in the $N$ band, although there is some residual curvature. We compare our measurements to theory, and make predictions for ELT Strehls and image FHWM with and without an atmospheric dispersion corrector (ADC). We find that for many mid-IR applications, an ADC will be necessary on ELTs.

1. INTRODUCTION

As we approach the Extremely Large Telescope (ELT) generation of telescopes, adaptive optics is becoming increasingly important to the general astronomical community. Large telescopes have small diffraction limits, and achieving these limits is a major goal for instrument builders. The mid-infrared wavelengths, in particular, stand to gain substantially from larger telescopes—at the diffraction limit, signal-to-noise ratio (S/N) $\propto$ Diameter$^2$ for background-limited observations of point sources. Today’s ∼8 m class telescopes are close to diffraction limited in the mid-infrared, even without adaptive optics, but maintaining the diffraction limit as telescopes continue to scale upwards will be challenging.

For ground-based telescopes in the mid-infrared, seeing is often considered a minor effect, and other (smaller) atmospheric effects are completely ignored. Kendrew et al. (2008) have predicted several atmospheric properties that may limit image quality on ELTs, including mid-infrared atmospheric dispersion, visible atmospheric dispersion for wavefront sensing, and water vapor turbulence (see Devaney et al. 2008 for a similar discussion in the near-infrared). So far, these effects have not been adequately measured.

The 6.5 m MMT, with its unique mid-IR adaptive optics system (MMTAO) provides a powerful testbed for mid-IR AO on ELTs. Effects that will severely limit image quality on ELTs are just measurable with MMTAO due to its highly stable point-spread function (PSF). By removing the largest atmospheric effect (seeing), we measure the second largest effect (atmospheric dispersion) with the newly commissioned spectroscopic mode.

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1The observations reported here were obtained at the MMT Observatory, a facility operated jointly by the Smithsonian Institution and the University of Arizona.

2In this article, we use “refraction” to refer to the absolute bending of light and “dispersion” to refer to the differential chromatic bending of light. Generally, theoretical considerations use refraction while practically, telescope images are affected by dispersion.
of the MMT’s Mid-Infrared Array Camera (MIRAC4-BLINC) and adaptive optics.

Atmospheric refraction is a well-known phenomenon at visible wavelengths, where it is typically treated as a smooth curve that flattens quickly longward of $K$ band (Edlén 1966; Ciddor 1996; Bönsch & Potulski 1998). However, more detailed treatments show that molecular resonances from CO$_2$ and H$_2$O (among others) dominate the infrared refraction curve (Hill & Lawrence 1986; Mathar 2004; Colavita et al. 2004; Mathar 2007). These authors show that each infrared window ($L$, $M$, $N$) is bracketed by molecular absorption and has an atmospheric refraction curve characterized by an S-shape superimposed on a stronger linear trend.

In this article, we measure the atmospheric dispersion curve on the short wavelength side of $N$ band (8.26 $\mu$m–11.27 $\mu$m) using spectroscopy and adaptive optics. In previous studies, Livengood et al. (1999) measured refractivity at one wavelength (12 $\mu$m) while Tubbs et al. (2004) interferometrically measured refraction throughout the $N$ band but were insensitive to the overall trend. Our spectroscopic result has the benefit of measuring all wavelengths simultaneously, so that the overall trend and curvature of the effect throughout $N$ band is unambiguous. By directly measuring the atmospheric dispersion curve, we can assess how the effect will limit image quality in the mid-infrared for ground-based ELTs. This is useful for instrument builders, who will have the option of using atmospheric dispersion correctors (ADCs) to suppress the effect.

2. OBSERVATIONS AND INSTRUMENT DESCRIPTION

Our data were obtained 2009 March 4 UT with the 6.5 m MMT and its deformable secondary adaptive optics system (MMTAO—e.g., Lloyd-Hart 2000; Wildi et al. 2003; Brusa et al. 2004). We used the newly commissioned spectroscopic mode of MIRAC4-BLINC. The instrument is a combination of the Mid-IR Array Camera, generation 4 (MIRAC4) and the Bracewell Infrared Nulling Cryostat (BLINC—Hinz et al. 2000), which for these observations is used in its “imaging” mode. MIRAC4 is functionally similar to previous incarnations of MIRAC (e.g., Hoffmann et al. 1998) with the main new feature being a DRS Technologies 256 $\times$ 256 Si:As array. Some of the relevant details of this new instrument are described in this section.

MIRAC4-BLINC was used to observe the mid-infrared standards $\alpha$ Her and $\gamma$ Aql. Both targets were bright in the visible (3.06 and 2.72 $V$ magnitudes for $\alpha$ Her and $\gamma$ Aql, respectively), which allowed us to run the MMTAO system at full sampling speed (550 Hz). At longer wavelengths, the MMTAO system can produce nearly perfect diffraction-limited images with extremely stable point-spread functions (Kenworthy et al. 2004; Hinz et al. 2006). At $N$ band, typical Strehls of up to $\sim$98% can be obtained under good seeing conditions (Close et al. 2003). Conditions were nonphotometric with moderately high winds (bursts up to 30 mph). However, the adaptive optics system was consistently able to stay locked on bright sources. Data from the MMT weather station showed an average temperature of 7.8°C, an average pressure of 745 mbar, and an average relative humidity of 44.3%. Detailed weather descriptions for each observation are shown in Table 1.

The MIRAC4-BLINC optics are enclosed and cooled in two attached cryostats. Reflective reimaging optics in the BLINC portion of the system create an image of the secondary on an articulated mirror. The mirror provides rapid chopping capability at rates of 1–10 Hz. A mask overlaid on the mirror provides the critical cold stop for the system. Downstream from the chopping mirror, an image of the telescope focal plane is formed at an f ratio of f/26.7 (1.22 mm$^{-1}$). A cold image stop wheel allows insertion of several slits at this location. A second set of reflective reimaging optics within the MIRAC4 cryostat create a second pupil image at a cold stop, which is followed by two filter wheels, the first of which contains a KRS-5 grism. The grism was fabricated by Zeiss and has an 11 degree wedge and 27 lines mm$^{-1}$ to create a first-order, low-resolution ($R \sim$ 100) spectrum on the detector. Flexure of the grism, with respect to the applications in this article, is negligible. By adjusting the position of the detector as well as a set of fold optics it is possible to create a range of magnifications from 0.55–1.1 (giving final plate scales from 0.054 to 0.11 pixel$^{-1}$ for the 50 $\mu$m pixels of the MIRAC4 detector).

| Table 1 | MMTAO OBSERVATIONS AND WEATHER (MARCH 4, 2009 UT) |
|---------|--------------------------------------------------|
| Object  | Air Mass | Exposure Length (s) | Number of Exposures | Pressure (mbar) | Temperature (°C) | Relative Humidity (%) |
| $\alpha$ Her | 1.05 | 0.05 | 80 | 745.1 | 8.0 | 42.1 ± 0.5 |
| $\alpha$ Her | 1.32 | 0.05 | 80 | 745.0 | 7.5 | 49.2 ± 1.5 |
| $\gamma$ Aql | 1.53 | 3 | 16 | 745.1 | 8.1 | 44.4 ± 0.4 |
| $\gamma$ Aql | 1.82 | 3 | 26 | 745.0 | 7.8 | 36.7 ± 1.3 |
| $\gamma$ Aql | 2.53 | 3 | 16 | 744.8 | 7.6 | 49.3 ± 0.5 |

Note: Values listed for air mass, pressure, temperature, and relative humidity are averages over each group of observations, with the error bars on relative humidity showing the standard deviation of the range of measured values over each group of observations. The weather data were recorded outside the telescope dome using a standard weather monitoring station on a 20 foot pole. All data were taken with an AO loop speed of 550 Hz.

2009 PASP, 121:897–904
For these observations we used the high-magnification setting of the camera to maximize our PSF sampling. At maximum magnification the grism dispersion is 12.6 nm pixel⁻¹. We used an off-center, 0.6 mm wide (0.73″) slit that placed the spectrum from 8.26–11.27 μm on the array. At 10 μm wavelength this gives a diffraction-limited spectral resolution of 130. The dispersion and range of the spectra were calibrated by using a thin transmissive piece of polystyrene and correlating the known spectrum of the film with the measured response of the system.

We aligned the target in the slit for both nod beams (see Fig. 1), chopping perpendicular to the slit and nodding along the slit. The slit was aligned perpendicular to the horizon in order to optimally measure atmospheric dispersion. Details of our observations are listed in Table 1.

The data were reduced using our custom artifact removal software described in Skemer et al. (2008). The images were then cross-correlated (with spline interpolation) and median combined (see a reduced image in Fig. 2).

3. ANALYSIS

In order to determine the intrinsic curvature of the MIRAC4 grism, we assume the α Her data taken at 1.05 air masses is unaffected by atmospheric dispersion. The models of Mathar (2004, 2007) suggest that the effect is small, but nonnegligible (see Fig. 3). As a result, all of our measurements underestimate the effect of atmospheric dispersion by the amount shown in Figure 3 at each air mass (a cumulative effect of 0.015″). In the interest of not contaminating our measurements with models, we ignore the effect for the rest of the analysis section. However, we do include the extra atmospheric dispersion in our ELT implications section.

We measure the trace of the grism by centroiding every wavelength with a best-fit, Moffat function (Markwardt 2009). Four parameters (peak value, centroid, FWHM, and Moffat Index) were allowed to vary with wavelength, with centroid being the relevant parameter. In principle, this fit could be used to produce an error estimate derived from random (i.e., photon) noise. However, our dominant error source is systematic noise caused by PSF-mismatch (described in this section). The grism trace is shown in Figure 4 and shows a 0.05″ offset over the range of our spectrum. The linear trend is the result of grism alignment and the curvature of the trace is intrinsic to the optical system. Two dips appear in our raw spectrum, which correspond to apparent artifacts in the grism trace. Since our PSF is a spectrally smoothed two-dimensional image, spectral features can easily cause slight PSF mismatches, which manifest themselves as grism trace artifacts. These regions are ignored in any further analysis.

For each observation listed in Table 1, we repeat the trace measurement, and subtract the grism’s intrinsic curvature (the trace of the 1.05 air mass spectrum; Fig. 4). This gives us a direct measurement of the atmospheric dispersion across our spectral range (minus the atmospheric dispersion at 1.05 air masses). The effect is fixed to 0 at the red end (11.2 μm) of our spectrum and is shown for each observed air mass in Figure 5. There is clear evidence that the blue light is refracted more than the red, and that this trend increases with air mass. A fit of the linear trend between 9.9 and 11.0 μm gives 10.3 mas μm⁻¹, 20.4 mas μm⁻¹, 15.8 mas μm⁻¹ and 33.9 mas μm⁻¹ at 1.32 air masses, 1.53 air masses, 1.82 air masses, and 2.53 air masses, respectively. We note that the observed trend is not perfectly sequential, as our 1.53 air-mass data appear to have experienced more atmospheric dispersion than our 1.82 air-mass data.

The strong linear trends from Figure 5 imply that atmospheric dispersion is an important effect to consider when...
designing mid-IR instruments on large telescopes. For the next (ELT) generation of telescopes, a mid-IR ADC will be necessary to achieve diffraction-limited images. However, traditional ADCs can only correct linear atmospheric dispersion. In Figure 6 we show the curvature of atmospheric dispersion by subtracting off a linear trend from the data shown in Figure 5. This simulates the effect of atmospheric dispersion after correction from a perfectly tuned ADC. Unfortunately, some elongation of the PSF may still occur in broad filters, even with an ADC, due to nonlinear atmospheric dispersion. Note that the observed curvature is sequential with air mass.

**Fig. 3.**—Theoretical atmospheric dispersion across our spectroscopic band at 1.05 air masses from the models of Mathar (2004, 2007). Our measurements subtract the atmospheric dispersion at 1.05 air masses so that we can measure our grism’s intrinsic alignment/curvature. This means our measurements consistently underestimate atmospheric dispersion by the amount shown in this plot (~0.015”).

**Fig. 4.**—(Top) N-band spectrum of α Her taken at 1.05 air masses. The spectrum has not been flux calibrated, and shows two large features: at ~8.8 μm, there is a detector quantum efficiency drop and at ~9.7 μm there is telluric ozone absorption. (Bottom) Grism spectral trace of α Her at 1.05 air masses (where atmospheric dispersion is assumed to be low; see Fig. 3). The trace features coincident with the MIRAC quantum efficiency (QE) effect and telluric ozone are artifacts.

**Fig. 5.**—MIRAC4-BLINC/MMTAO measurements of atmospheric dispersion in the N band. For each air mass, we measure the grism trace and subtract the grism’s intrinsic curvature (Fig. 4). The effect has been fixed to 0 at 11.2 μm. Our results show that atmospheric dispersion in the mid-infrared is a relatively large effect, although it is considerably smaller than the ~0.3” diffraction-limited FWHM of a 6.5 meter telescope. On larger ELTs, mid-IR atmospheric dispersion will severely limit image quality if left uncorrected. Note that we underestimate atmospheric dispersion by the amount shown in Fig. 3 due to our assumption that atmospheric dispersion is negligible at 1.05 air masses.

**Fig. 6.**—On ELTs, mid-IR atmospheric dispersion correctors (ADCs) will be necessary to suppress the linear atmospheric refraction effect shown in Fig. 5. In this figure we fit and remove the linear trend from each atmospheric dispersion curve. The resultant nonlinear residuals will be uncorrected by traditional ADCs.
4. DISCUSSION

4.1. Fitting with Models

We compare our measurements to the models described by Mathar (2004, 2007). These models calculate refractive index values \((n)\) by summing over the electronic transitions of atmospheric molecular constituents from the far-ultraviolet to the far-infrared, using the molecular line database HITRAN (Rothman et al. 2005). A full description of the model can be found in Mathar (2004).

The refraction, or the angular distance between the true and apparent zenith distances for a given refractive index, can be calculated from

\[
R \approx 206.265 \left( \frac{n^2 - 1}{2n^2} \right) \tan(z),
\]

where \(z\) is the true zenith distance in radians and \(R\) is in arc-seconds. From this, the differential refraction (dispersion) between two wavelengths is given by

\[
R_1 - R_2 \approx 206.265 \left( \frac{n_1^2 - 1}{2n_1^2} - \frac{n_2^2 - 1}{2n_2^2} \right) \tan(z).
\]

We calculate the expected atmospheric dispersion using the output of Mathar’s models and equation (2) (where the value of \(n_2\) is fixed to the refractive index at \(\lambda = 11.2\) \(\mu\)m, as we did in
our differential MMTAO measurements). Because our measurements subtract off atmospheric dispersion at 1.05 air masses (assuming it to be small; see Fig. 3), we do the same with our models. The comparison between our measurements and the models is shown in Figure 7. The solid curves are our measurements, the dotted curves are the models with dispersion at 1.05 air masses subtracted, and the dashed curves are the models without dispersion at 1.05 air masses subtracted.

We ran the models at a variety of relative humidities to reflect the measured variation during each group of observations (see Table 1). These small humidity variations create a \sim 10\% model uncertainty for each set of observations.

The models show a good fit to the observed spectral trace longward of \sim 9.5 \mu m in three of the four cases (qualitatively, a quantitative approach, such as a \chi^2 test would be inappropriate given that our dominating errors are systematic). The clear exception is the spectral trace taken at air mass 1.53, which follows the same trend as the others but lies significantly above the curve predicted for the meteorological conditions at the time of observation. The discrepancy could be due to a temporary burst of moisture high up in the atmosphere (where our ground-based weather monitors are insensitive). It could alternatively be the result of a filter wheel return error which caused our grism to be slightly misaligned. This second scenario is unlikely as the filter wheel has a resolution of <0.03°, which should provide a spectrum tilt of, at most, 5 mas across the array.

At all four air masses, our measurements show more curvature than the models predict. At this point, it is unclear whether the source of disagreement is error in the measurements or error in the models. Given that the linear trend dominates the curvature, this disagreement may prove insignificant. However, if the linear trend is corrected with an ADC, the curvature may still cause some nonnegligible dispersion at very high air masses.

Overall, the Mathar models fit our measurements very well, and will be useful for ADC designs and operations. It is still an open question whether ground-based weather measurements will make good predictors of atmospheric dispersion throughout the atmosphere. In our case, ground-based weather measurements allowed accurate predictions in three out of four cases. The source of the residual curvature is also unclear at this point. Both issues should be addressed with future observations.

4.2. Implications for ELTs

Mid-IR cameras on ELTs will need to operate in several modes to accomplish a wide variety of scientific tasks. The loss of image quality related to atmospheric dispersion will affect each situation differently. Here we discuss specific implications to three commonly used mid-IR modes: broadband imaging, narrowband imaging, and spectroscopy.

4.2.1. Broadband Imaging

Using our MMTAO observations, we can simulate the degradation of image quality for ELTs. Our MMTAO observations only cover 8.26 \mu m–11.27 \mu m but the broad N-band extends all the way to \sim 14 \mu m. We approximate full N-band dispersion curves (8.26 \mu m–13.74 \mu m) by reflecting our MMTAO dispersion curves about 10.5 \mu m (creating the characteristic S-shape; this may be an oversimplification as Mathar’s (2004, 2007)

![Simulated three-color N-band images (blue is 8.26 \mu m and red is 13.74 \mu m) for a 42 m telescope at different air masses (zenith is up). Without an ADC, image quality will be significantly degraded in the altitude axis. The images assume a flat SED and a site similar to the MMTs.](image)

TABLE 2

| Telescope Diameter (m) | Air Mass | Strehl (%) | Strehl with ADC (%) | FWHM (mas) | FWHM with ADC (mas) |
|------------------------|----------|------------|---------------------|-------------|---------------------|
| 42                     | 1.0      | 100        | 100                 | 53          | 53                  |
| 42                     | 1.5      | 43         | 98                  | 135         | 54                  |
| 42                     | 2.5      | 27         | 94                  | 226         | 56                  |
| 30                     | 1.0      | 100        | 100                 | 74          | 74                  |
| 30                     | 1.5      | 56         | 99                  | 139         | 75                  |
| 30                     | 2.5      | 37         | 97                  | 225         | 77                  |
| 24.5                   | 1.0      | 100        | 100                 | 91          | 91                  |
| 24.5                   | 1.5      | 64         | 99                  | 145         | 92                  |
| 24.5                   | 2.5      | 44         | 98                  | 225         | 93                  |

Note.—The N-band filter is assumed to be rectangular from 8.26 \mu m–13.74 \mu m. We also assume a flat SED and a site similar to the MMTs. FWHM is measured in the altitude axis. In the azimuth axis, FWHM is assumed to be diffraction limited.
models show slightly increased curvature longward of 11 μm). We also add back the theoretical dispersion at 1.05 air masses having confirmed the validity of the linear trends in Mathar’s (2004, 2007) models. Finally, we fit the curves with a fifth-order polynomial to remove the noise and systematics shown in Figures 4–6.

We simulate ELT images by convolving our estimated dispersion curves with diffraction-limited PSFs and flat SEDs. In this case, the (one-dimensional) convolution step is simply adding together PSFs at positions defined by our dispersion curves. The PSFs are constructed from annulus apertures with outer diameters of 24.5 m, 30 m, and 42 m and a 20% central obscuration. An example of our simulated images is shown for a 42 m telescope with no ADC in Figure 8. The results show a severe elongation in the altitude axis.

Using our simulated ELT images, we measure Strehl and FWHM, with and without a linear ADC, at 1.0, 1.5, and 2.5 air masses. These results are shown in Table 2. Without a linear ADC, Strehl and FWHM are significantly degraded for all three telescopes, even at 1.5 air masses. With a linear ADC, the images are almost perfectly corrected at reasonable air masses. Thus, we conclude that a linear ADC is essential for broadband N-band imaging on ELTs and that a higher order, “non-linear” ADC is not.

4.2.2. Narrowband Imaging

We repeat the experiment from the previous section but with a 10% filter centered at 10.5 μm (note that no reflection of the atmospheric dispersion curve is necessary). Our results are shown in Table 3. Image quality is still noticeably degraded with the narrowband filter, but the effect only becomes serious for the largest (42 m) telescope. With an ADC, narrowband imaging is completely unaffected by atmospheric dispersion. Thus, we conclude that a linear ADC will be useful for some narrowband imaging applications on ELTs, and unnecessary for others based on scientific needs.

4.2.3. Spectroscopy

The chromaticity of the images shown in Figure 8 implies that chromatic slit loss may be a major problem for ELT mid-IR spectroscopy. The problem can be avoided by always keeping the slit perpendicular to the horizon so that there is no refraction in the spectral dispersion axis. However, this would preclude observations of a variety of spatially resolved objects (binaries, circumstellar disks, etc.) where a properly aligned position angle is important. Based on our predictions for broadband image quality (Table 2), a linear ADC would suppress dispersion to the point where broadband spectroscopy would be possible at different position angles, given a wide slit. For certain high resolution spectroscopic applications (with a very narrow bandpass), an ADC will not be necessary.

5. CONCLUSIONS

After seeing is removed by adaptive optics, atmospheric dispersion will be the dominant source of image quality degradation on ground-based ELTs, surpassing diffraction. While theory has predicted large S-shaped refraction curves in each infrared window, the effect had not been measured as a function of wavelength through the atmosphere. In this article, we use MMTAO and the MIRAC4-BLINC spectograph to measure atmospheric dispersion from 8.26 μm–11.27 μm. We find the following:

1. “Blue” light (8.26 μm) is refracted more than “red” light (11.27 μm) in the mid-infrared, and the effect increases with air mass and humidity.
2. Although the linear term of mid-IR atmospheric dispersion is dominant, a nonnegligible amount of curvature exists too. Observations over different wavelength ranges
(including full $N$ band) will help determine the source of this curvature.

3. The dominating linear trends in our measurements are in excellent agreement with the models of Mathar (2004, 2007). We measure more curvature than the theory predicts; however, the magnitude of the curvature is small compared to the linear trend. Mathar (2004, 2007) models may now be used to develop predictive models for ADCs given ground-based measurements of temperature, pressure, relative humidity and air mass.

4. Based on simulations of mid-IR ELT adaptive optics images with atmospheric dispersion, we find that ADCs will be useful for high-Strehl, narrowband imaging and spectroscopy, and essential for high-Strehl, broadband imaging and spectroscopy. Our conclusions are only based on an analysis of image quality. We make no claims about the technical feasibility (cost, increased background, decreased throughput, etc.) of a mid-IR ADC. Instrument builders will have to weigh these issues as well.

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2009 PASP, 121:897–904