Atmospheric Transmission and Thermal Background Emission in the Mid-IR at Mauna Kea

THIRTY METER TELESCOPE

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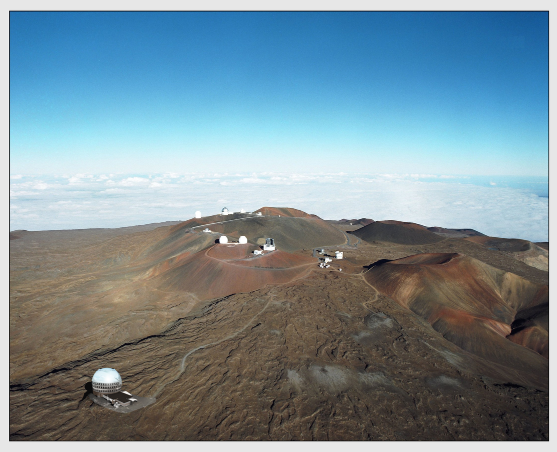

Introduction

The Thirty Meter Telescope (TMT) Project contemplates the development of mid infrared instrumentation (imaging and spectroscopy) for its second generation instruments. Observations in the mid-IR enable interesting science: evolution of gas and chemistry in protoplanetary discs – enabling the study of star and planet evolution, study of accretion and outflows around protostars, characterization of exoplanet atmospheres, detection of biomarkers from transmission spectral studies in exoplanet atmospheres, evolutionary connections of black holes & galaxies. Also, the mid-IR enables the study of moderate redshifted objects: "The [SIV] line (10.5μm) is an excellent substitute with superior ground-based sensitivity instead of the [OIV] line (Packham, et al., 2012)", as well as the dynamics and chemistry of regions highly obscured by surrounding dust, such as found in the central region of galaxies and star forming regions.

One important limiting factor in the observation at mid-infrared wavelengths (7 μm to 26 μm) from ground-based observatories is the water vapor in our atmosphere. The main limiting factors being: water vapor absorption – due to the complex ro-vibrational spectrum of water vapor molecules – and added noise in the detectors from atmospheric thermal emission.

Goals of this Study

◆Statistical characterization of the water vapor field at Mauna Kea.

◆Vertical distribution of absolute humidity at Mauna Kea.

◆Determination of the atmospheric transmission in the mid-IR for dry and median conditions of precipitable water vapor.

◆Determination of the atmospheric radiance in the mid-IR.

◆Learn about the mesoscale atmospheric dynamics that are associated with low and high values of precipitable water vapor by the location of Mauna Kea.

Datasets

For the statistical characterization of water vapor, we make use of the following sources of information:

•The surface absolute humidity measurements that were derived from temperature and relative humidity observations (Otárola et al, 2010) at the 13N site during the TMT site testing campaign (Shöck, M. et al., 2009).

•The precipitable water vapor (PWV) observations derived from the monitoring of optical depth using a 225GHz tipping radiometer (MacKinnon M., 1988), by the location of the Caltech Submillimeter Observatory (CSO) at Mauna Kea. The relation for deriving PWV from 225 GHz optical depth utilized for this analysis is: **PWV = 21.422 x τ_{225GHz} - 0.2958** (Radford, S., *Private Communication*).

•Radiosonde soundings from Station (91285; PHTO), Hilo (HI), obtained from http://weather.uwyo.edu/upperair/sounding.html.

•Mesoscale analyses data available from the European Center for Medium Range Weather Forecast (ECMWF) available from http://apps.ecmwf.int/datasets/.

Methodology

For the characterization of PWV, standard statistical analysis was used. For the determination of the atmospheric transparency and atmospheric radiance for the mid-infrared up to the far-infrared bands, the following steps were performed:

•The radiosonde soundings were used to obtain a typical vertical profile of atmospheric temperature and absolute humidity for the Mauna Kea site. Best conditions for observations in the mid-IR are during winter, with low PWV and cold atmospheric temperatures. Thus, minimizing the atmospheric absorption of mid-IR cosmic signals and thermal emission from the atmosphere that contributes to a higher thermal noise in mid-IR bands. The profiles, in the upper atmosphere (up to 90km), were complemented with data from the US standard atmosphere for winter conditions (Seinfield, J. H. & Pandis, S. N., 1998). The absolute humidity profile was normalized, and subsequently adjusted for any desired level of integrated precipitable water vapor.

•A line-by-line, layer-by-layer radiative transfer model, implemented in Matlab, making use of HITRAN (Rothman, L, et al., 2009) spectral line information, was used to derive the layer and total atmospheric transmission spectra.

•The total atmospheric radiance was obtained by computing the atmospheric emission, for each atmospheric layer, and multiplying the layer emissivity by the Planck function as a function of wavelength & the physical temperature of each corresponding layer. The total atmospheric radiance is the result of adding that of all layers.

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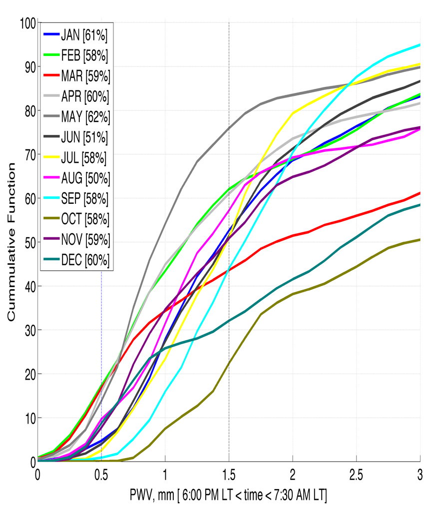
Results & Analysis

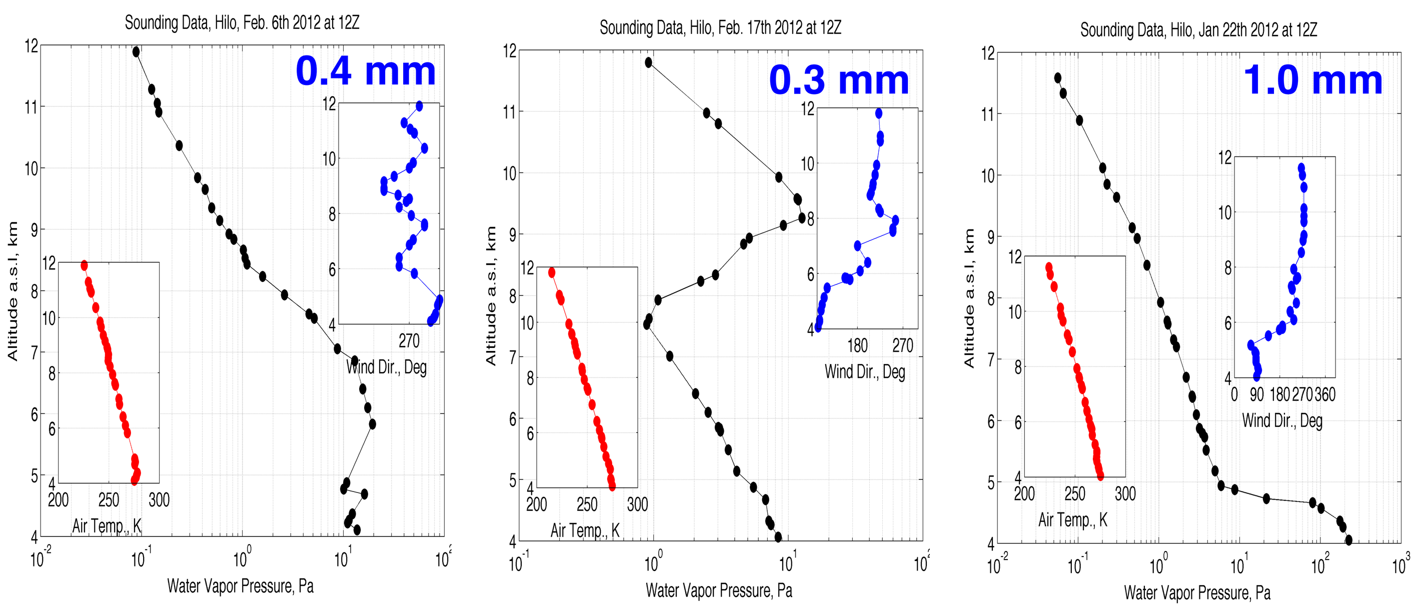
As for the statistical characterization & vertical distribution of water vapor: At the location of the TMT site (ϕ=+19.8330º N; λ=155.4810º W), PWV is ultimately derived from 2-min averages of surface measurements of air temperature and relative humidity, obtained during the TMT site testing campaign in the period 2005/06/29 – 2007/12/31 (*see Otárola, et al., 2010 for details on how to infer PWV from surface water vapor density*). Table 1 shows the statistical percentiles of PWV out of 352534 values of PWV (only data in the period 6:00 PM to 7:30 AM are used for the statistics). Figure 1, shows the cumulative function of PWV for every month in 2012, computed from PWV derived from measurements of optical depth at 225 GHz from the Caltech Submillimeter Observatory (CSO) site, located several hundred meters west of the 13 N site.

How water vapor gets distributed with altitude is important in the mid-IR: *near surface water vapor leads to higher atmospheric thermal radiance and broader water vapor absorption lines, the opposite is true when water vapor gets distributed to higher levels above the surface.* Below, a few examples of water vapor vertical distribution during January and February 2012 are shown; they are derived from Radiosonde Soundings from Hilo Station.

TABLE 1

PCTLE	PWV
5%	0.6 mm
10%	0.7 mm
25%	1.0 mm
50%	1.8 mm
75%	3.8 mm





Atmospheric Transmission & Atmospheric Radiance: A line-by-line, layer-by-layer radiative transfer model, using the HITRAN spectral database for H_2O, CO_2, CO, CH_4, O_3, O_2, N_2O (at high spectral resolution and including all isotopes) was implemented in Matlab. The model was run for two cases of PWV, a dry case (0.3 mm) and a near median condition (1.5 mm). The atmospheric transmission & atmospheric radiance were computed following the model shown below:

$$Tr_i(\lambda) = e^{-(\alpha_{H2O}(\lambda)+\alpha_{CO2}(\lambda)+\alpha_{CO}(\lambda)+\alpha_{CH4}(\lambda)+\alpha_{O3}(\lambda)+\alpha_{O2}(\lambda)+\alpha_{N2O}(\lambda))dH_i}$$

$$\alpha_{mol}(\lambda) \propto S_{0,mol}(T_i)\cdot N_{mol}\cdot f(\lambda-\lambda_0)$$

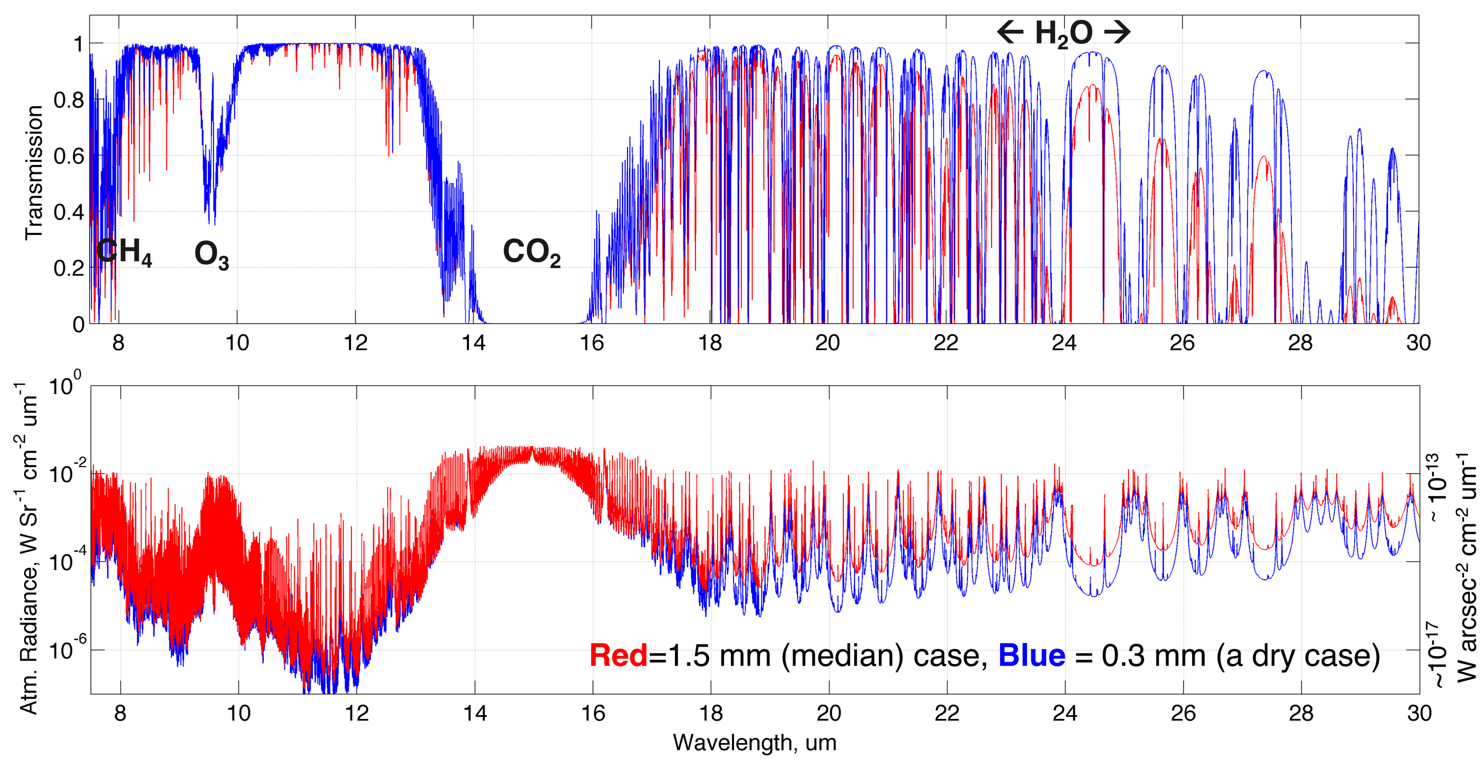
$$absorptivity + transmission = 1$$

$$emmisivity = absorptivity$$

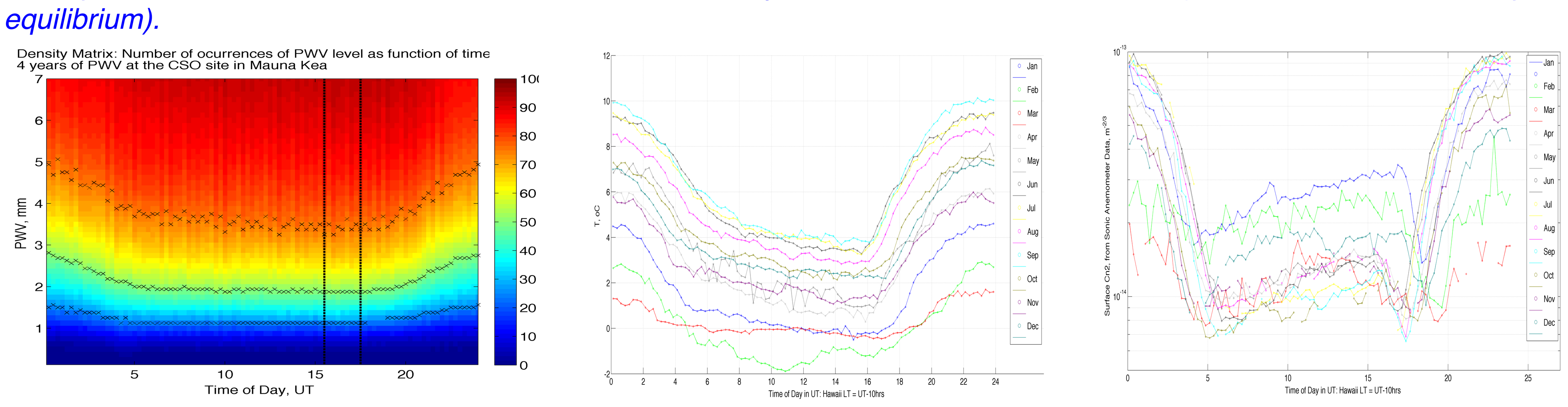
$$\rightarrow emmisivity_i(\lambda) = \{1 - Tr_i(\lambda)\}$$

$$R_i(\lambda) = emmisivity_i(\lambda)\cdot\left\{\frac{2\pi hc^2}{\lambda^5}\cdot\frac{1}{e^{hc/\lambda kT}-1}\right\}$$

$$R_{total}(\lambda) = \sum_{i=1}^{N=58}\left\{R_i(\lambda) * \prod_{j=1}^{j=i-1} Tr_j(\lambda)\right\} \quad \text{if } i-1 < 1 \text{ } Tr_j(\lambda)=1$$



A proposal for using the twilight time for observation in the mid-IR bands: The mid-IR community has proposed that one way of maximizing the scientific output of a telescope could be by using about 1-2 hours of observing time available in the evening and/or morning twilights (one example is TEXES at the ITRF). This has motivated the community to look at how the PWV, air temperature and turbulence looks as a function of hour through the day. These parameters are shown below for the Mauna Kea site. *The results show PWV is the lowest by the morning twilight (likely because water vapor gets trapped below a low-altitude temp. inversion layer), similarly, the air temperature is the lowest & telescope structures have time to reach thermal equilibrium with the environment (minimizing this way their radiances and background thermal noise), and low-level atmospheric turbulence is the lowest due to lower variability in the index of refraction field (as a result of the air temperature equilibrium).*



Would it be possible to predict periods of low PWV?: The atmosphere is highly unsaturated, and the atmospheric water vapor is limited by the air temperature through energy considerations (as shown in the Clausius –Clapeyron equation). Local sources of water vapor, originating from sublimation of snow/ice, and evaporation of surface waters as well as diffusion of water vapor from sub-surface, are to be considered in very dry sites. *However, the water vapor field is dominated by synoptic and mesoscale dynamics, where the location of high & low pressure centers respect to a site location become very relevant in the advection of cold/dry or warm/wet air (see examples below): So definitely, PWV can be forecasted by means of a mesoscale model (Chacón, A. et al., 2011, Pozo, D., e al., 2011).*