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ANALYSIS OF THE VERTICAL PROFILES OF HUMIDITY FROM RADIOSONDE SOUNDINGS LAUNCHED FROM ANTOFAGASTA

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RESUMEN

La región del Desierto de Atacama en el norte de Chile alberga algunos de los más recientes observatorios astronómicos, equipados con instrumentos que cubren varias bandas espectrales de interés, incluyendo: microondas, milimétrica, sub-milimétrica, infrarrojo medio, infrarrojo cercano y visible. Entre otros, la región hospeda al *Very Large Telescope (VLT)* ubicado en Cerro Paranal, al Gran Arreglo Milimétrico de Atacama (ALMA), actualmente en construcción en el LLano de Chajnantor en la ladera occidental de la cordillera de Los Andes, y ha sido la región seleccionada para la instalación del Telescopio Europeo Extremadamente Grande (E-ELT). Debido al rol del vapor de agua atmosférico como una fuente de absorción de radiación en varias bandas espectrales, además de introducir fluctuaciones de fase en el frente de onda detectado por interferómetros tal como ALMA, hace del estudio de vapor de agua atmosférico un tema relevante en esta región. Este trabajo presenta un análisis de los perfiles verticales de humedad obtenidos por medio de radiosondas lanzadas desde las cercanías de la ciudad de Antofagasta, y se focaliza en la magnitud del sesgo seco en los perfiles de humedad relativa que se origina en un cambio de temperatura de los sensores de humedad relativa, respecto al ambiente circundante, producido por radiación solar directa sobre los sensores.

ABSTRACT

The Atacama Desert region in northern Chile is a host to some of the most recent astronomical observatories, equipped with instrumentation covering several spectral bands of interest, including: microwaves, millimeter, sub-millimeter, mid-infrared, near-infrared and visible. Among others, the region host the Very Large Telescope (VLT) located at Cerro Paranal, the Atacama Large Millimeter Array (ALMA), under construction at the Llano de Chajnantor plateau in the west slope of the Andes Mountains, and it has been selected the region for the future installation of the European Extremely Large Telescope (E-ELT). Because of the role of atmospheric water vapor as a source of absorption of electromagnetic radiation in several of the spectral bands, as well as of phase fluctuations for an interferometer such as ALMA, makes the study of atmospheric water vapor a relevant topic in this region. This work presents an analysis of the vertical profiles of humidity from radiosonde soundings launched from nearby the city of Antofagasta, and looks into the magnitude of a dry-bias in the relative humidity (RH) profiles arising from a change of temperature of the RH sensors, respect to the surrounding ambient due to solar heating.

Key Words: atmospheric effects — site testing

1. INTRODUCTION

Water vapor in the Earth's atmosphere is the dominant source of absorption of radiation and increased thermal background in the Mid-Infrared (MIR) spectral band (Chamberlain et al. 2000). It is also the most important source of absorption of radiation in the millimeter and sub-millimeter wavelength spectral bands; and, fluctuations of water vapor across the aperture of an aperture synthesis radio array (such as ALMA), introduces phase fluctuations that degrade its image quality and sensitivity(Olay 1998; Radford & Holdaway 1998).

This work focuses in the analysis of atmospheric vertical profiles of humidity obtained by means of radiosonde soundings from the station of Antofagasta, with emphasis in the effect of a known dry bias in the RH sensors on the statistics of precipitable water vapor (PWV). PWV is computed from the vertical integration of the water vapor density (WVD) profile, which in turn is derived from the vertical profiles of temperature and RH as shown in Otárola et al. (2010) and Otárola, Querel, & Kerber (2011).

The Antofagasta radiosonde sounding station has been assigned by the World Meteorological Organization (WMO) the identifier SCFA and station number 85442. Table 1 shows its main parameters, as well as a time history of the radiosonde sensor pack-

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TABLE 1

MAIN PARAMETERS OF ANTOFAGASTA RADIOSONDE SOUNDING STATION

Parameter	Type/Value	Notes
Station Identifier	SCFA	...
Station number	85442	WMO ID
Latitude	23°27′01″	South
Longitude	70°26′27″	West
Altitude	120 m	Above Sea Level
Obs. Time	12 UT	Daily
Sensor Package	VIZ (Sippican)	1980–1988
Sensor Package	RS80 & RS80-G (VAISALA)	1988–05/2005
Sensor Package	RS92-SGP(VAISALA)	06/2005–Present/2011

ages that have been used at this station (Juan Aravena, private communication).

1.1. *Relative Humidity Sensors and Dry Bias*

An important part of the community in the field of atmospheric sciences and astronomy uses Vaisala© radiosonde sounding packages. Regarding the technology, the Vaisala© RH sensors consist of a thin-film capacitive sensor that is made of a polymer layer sandwiched between the porous electrodes of a capacitor. The sensor changes its capacitance depending on the amount of water vapor molecules that diffuse from the environment into the polymer material.

Because of the relevance of the scientific applications for these sensors, where high accuracy in the determination of the atmospheric humidity profile is required, several authors have compared the output from several models of Vaisala© RH sensors to other more complex instruments of known accuracy, such as: cryogenic frostpoint hygrometers (Miloshevish et al. 2004, 2009; Vömel et al. 2007), other calibrated thin-film capacitive polymer sensors (Leiterer et al. 2005), and to microwave radiometers (Turner et al. 2003).

Some of the most important problems affecting this particular kind of RH sensor, that have been identified and described in detail, are the following: calibration model inaccuracy in the response of the sensor with actual environmental temperature, chemical contamination of the polymer (binding sites within the polymer are used by molecules from the sensor's package rendering these sites unavailable for water molecules), sensor aging (sensor response to temperature changes over time affecting its calibration), response time of the sensor changes with temperature (usually resulting in a slower response time with lower temperatures), and also importantly a solar-heating that changes the temperature of the RH sensor with respect to the surrounding environmental temperature and therefore bias the determination of the RH towards drier values (as cited in Otárola, Querel, & Kerber 2011).

The two most important effects that contribute to a dry bias in the RH measurements are: the solar-heating of the RH sensor and the response time of the sensors as a function of temperature (Miloshevish et al. 2004, 2009; Vömel et al. 2007). Of these two effects, for daytime radiosonde launches, the most relevant is the dry-bias introduced by solar-heating of the RH sensor. The magnitude of the dry bias for radiosondes launched at 12 UT from Antofagasta (about 9:00 AM local time) is explored in the next section. The dry-bias that arises from the decrease in the response of the RH sensor with low temperatures is most important in the atmosphere at heights above 14 km ($T < -68°$) (Vömel et al. 2007). At sites of interest for astronomy there is very little water vapor above 14 km that contributes to the PWV in the atmospheric column, and therefore this second effect is neglected in this analysis.

2. THE MAGNITUDE OF THE SOLAR-HEATING RH DRY BIAS FROM THE ANTOGASTA RADIOSONDE SOUNDINGS

Table 1 shows that the Antofagasta sounding station have been using RS92-SGP Vaisala© RH sensors since June 2005. A correction model for the dry-bias introduced by solar heating, of the RS92 type sensor, was published in the work of Vömel et al. (2007). This model was used to correct 958 RH profiles obtained from radiosonde soundings

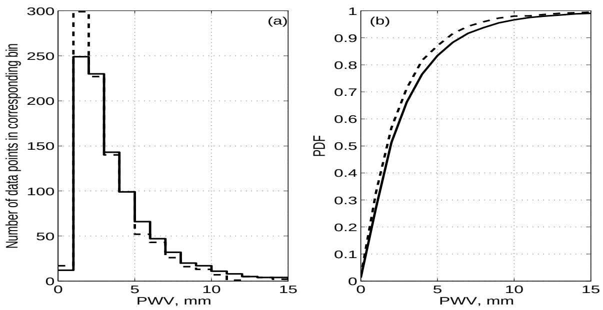

Fig. 1. (a) Histogram and (b) Probability Density Function of Un-corrected (dashed) and Corrected (solid) data of PWV from the analyses of radisonde soundings launched from the station of Antofagasta (SCFA, 85442), in the period July 2005–October 2010. The RH sensors in this period was of the type Vaisala© RS92.

launched from the Antofagasta station in the period July/2005–October/2010 and that covered the whole atmosphere up to 14 km above sea level (ASL). The 958 soundings correspond to 73% of those available in this period of time, and to 49% of the total number of soundings possible in this time span.

2.1. *Data Analysis*

The radiosonde soundings data for the period July/2004–October/2010 was extracted from the repository provided by the Department of Atmospheric Sciences at the University of Wyoming[2]. The soundings were inspected to select all of those that covered, at least, the vertical altitude range from 3 km till 14 km ASL. As explained in the previous paragraph a total of 958 soundings met this criteria.

For the purpose of this study, the 958 radiosonde profiles were linearly interpolated to a vertical resolution of 25 m. The section of the temperature and original (uncorrected) RH profiles between 3 km m and 14 km m altitude ASL was used to compute the vertical profile of WVD. The derivation of the WVD profile follows the same formulation shown in the set of equations (3) in Otárola et al. (2010). The vertical integration of the WVD profile in the given altitude range provides the original PWV data series.

In a subsequent step, the RH profiles were corrected for the solar-heating dry bias using the model explained in the work of Vömel et al. (2007). As in the first case, the temperature profile, this time together with the corrected RH profile, were used to compute a set of corrected WVD profiles. The vertical integration of the corrected WVD profiles provided a data series of corrected PWV.

[2]`http://weather.uwyo.edu/upperair/sounding.html`.

TABLE 2

STATISTICS OF PWV OBTAINED AT THE ANTOFAGASTA SOUNDING STATION

Parameter	Original Dataset	Corrected Dataset
1st Quartile	1.2 mm	1.4 mm
2nd Quartile	2.1 mm	2.5 mm
3rd Quartile	3.8 mm	4.3 mm
Mean	3.0 mm	3.4 mm

Finally, the two data series of PWV (original and corrected) are used to compute the magnitude, in terms of PWV, of the dry-bias due only to the solar heating of the RH sensor.

The reason for to obtain the PWV from the integration of the profile from 3 km and above, is due to that 3 km is the altitude of the Armazones site. This is located at about 100 km due SSE from the city of Antofagasta and it was one of the sites studied by the Thirty Meter Telescope (TMT) project and is currently the site decided for the construction of the European Extremely Large Telescope (E-ELT). These are two of the most recent large aperture projects for astronomy in the visible to mid-infrared spectral range for which water vapor is a relevant variable (see the works of Shöck et al. 2011 and Melnick 2011).

2.2. *Results*

Figure 1 shows the statistical histogram and the probability density functions computed for the PWV data-series derived from the original and corrected RH profiles. Similarly, Table 2 summarizes the statistical quartiles and the mean values for the corresponding PWV data-series.

The results, after correcting for the dry-bias, show in general an increase of about 0.3 mm in PWV between 3 km and 14 km altitude. The relative importance of this difference lies on the percentage of the time that observatories such as the Very Large Array (VLT) and the projected E-ELT plan to dedicate to astronomical observations in the mid-infrared, where absorption of radiation of astronomical sources and added thermal emission by water vapor is more relevant. Perhaps, the relevance of these statistics is more important for those modeling the performance of mid-infrared camera & spectrographs, currently in the design phase, where typically either median or mean values of PWV are used.

The 0.3 mm represents an increase of 14.3% of the uncorrected median PWV value. When using radiosonde soundings launched from the station of Antofagasta to infer/extrapolate the PWV at sites of astronomical interest in this region, there are also other factors that have to be considered such as: the spatial and temporal variability of the humidity field. For instance, the PWV at two sites separated by 100 km (such as is the distance between the city of Antofagasta and the Armazones/Paranal area), the absolute humidity can differ in the order of 20% at 1σ level as stated in the work of Otárola, Querel, & Kerber (2011).

3. FINAL CONSIDERATIONS AND CONCLUSIONS

Is important to notice that the dry-bias correction used in this study (that in Vömel et al. 2007) doesn't account for the effect of the Sun's elevation angle on the illumination of the RH sensor. A more recent model (Miloshevish et al. 2009) accounts for this effect but the implementation and testing of the algorithm was not yet completed by the time of the analysis of the Antofagasta data. The expected result is that higher the elevation of the sun, higher also is the magnitude of the dry-bias due to solar heating of the RH sensor. The radiosonde soundings at the city of Antofagasta are launched daily at 12:00 UT, which correspond to 8:00 AM local time in the fall/winter seasons and 9:00 AM local time in the spring/summer seasons. In average through the year, the sun rises at about 7:15 local time. Therefore, the sun elevation angle at the time of the radiosonde launch (and during its flight, approximately 45 minutes) ranges from about 11° to 23° during the fall/winter season, and from about 26° to 38° in the spring/summer season. Consequently, the dry-bias due to solar heating is likely to be more important during the spring/summer months.

The solar heating of the RH sensor requires direct illumination of the sensor by the sun, this is only possible in clear weather. The atmospheric conditions in Antofagasta are dominated by a subsidence temperature inversion and an extended maritime stratocumulus cloud deck with ceiling at about 1.5 km ASL (Muñoz, Zamora, & Rutllant 2011), with mostly clear atmosphere above it. Therefore, the first 1.5 km section of the RH soundings shouldn't be affected much by a solar heating because of two reasons, (1) the relatively low elevation angle of the sun, and (2) the fact the sounding is not receiving direct sun illumination because it is under the ceiling of the maritime cloud deck.

Another important consideration has to do with the reproducibility of the RS92-SGP RH sensors. The reproducibility[3], as quoted in the sensor's specification provided by Vaisala©, is of 2% of RH, i.e., two twin radiosonde soundings probing the same atmospheric column could show a departure of 2% of RH to a 1σ level. In this study, a Monte Carlo analysis was conducted by taking the 948 radiosonde soundings and algebraically adding, at each point in the original RH profile, a RH offset selected randomly from a Gaussian distribution of zero mean and 2% RH standard deviation. The temperature profile and the modified RH profile were used to compute the PWV by integration of the WVD profile from 3 km to 14 km ASL. The net result was that the 2% RH reproducibility translates into a 2% uncertainty in the PWV, i.e. the reproducibility uncertainty is smaller in magnitude than the 14.3% effect due to the dry-bias induced by solar heating of the sensor.

In summary, this work shows that the dry-bias effect affecting daytime radiosonde RH soundings is important and can't be neglected. Accurate measurements of PWV are specially relevant for the characterization of geographic locations for the installation of millimeter, submillimeter, and mid-infrared ground-based astronomy facilities, and even more when using radiosonde soundings for climate studies.

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