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Measurements of Precipitable Water Vapour for the Africa Millimetre Telescope

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Precipitable Water Vapour (PWV) is the main source of opacity in millimetre and sub-millimetre observations. Thus, before establishing a millimetre or sub-millimetre observatory, evaluating the PWV above the location is crucial. This paper presents the results of ongoing measurements of PWV in two potential locations for the Africa Millimetre Telescope (AMT), using ground-based instruments available on site namely, AErosol RObotic NETwork (AERONET) and Autonomous Tool for Measuring Observatory site COnditions PrEcisely (ATMOSCOPE) and the H.E.S.S. weather stations. All measurements were taken at the High Energy Stereoscopic System (H.E.S.S.) observatory and for Mt. Gamsberg, PWV was estimated using the scaling method. The preliminary findings of this study show that the H.E.S.S. site has a slightly higher yearly median PWV than the former site of the SEST telescope at La Silla, with Mt. Gamsberg reaching even lower values by scaling to its elevation. However, in-situ measurements are recommended to validate the scaled results.

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1. Introduction

The Event Horizon Telescope is a network of mm-wave telescopes across the globe that are used to image super-massive black holes (SMBHs). In 2017, the EHT observed the shadow of the central black hole in the radio galaxy M87, M87*, and the one in our own Milky Way, Sgr A*, the results of which were published in 2019 and 2022, respectively [1, 2]. The horizon-scale variability of Sgr A* on sub-hour timescales and the sparsity of the EHT array, limiting its imaging capabilities, particularly during the first hours of observations led to the proposal for the Africa Millimetre Telescope (AMT) [3]. In [4] it was shown that adding the AMT will lead to robust images during those initial observation hours. To increase the sensitivity of the EHT for temporal variability, also other potential sites for new antennas to be added to the current network have been identified [5]. The AMT is envisioned as a 15 m-diameter telescope that is planned to be built in the Khomas Highlands of Namibia and will be the first mm-wave telescope in Africa. Apart from conducting very-long baseline interferometry (VLBI) at 230 GHz and possibly at 345 GHz as part of the EHT, the AMT will also conduct single-dish flux monitoring of Active Galactic Nuclei (AGN) [6] and transient science [7]. Two sites within the Khomas Highlands have been identified to possibly host the AMT: a site close to the High Energy Stereoscopic System (H.E.S.S.)[1] and atop of Mt. Gamsberg.

Mt. Gamsberg and the area surrounding it have long been known for excellent astronomical quality (see [3] and references therein). Still, only a single study on the amount of precipitable water vapour (PWV) has been conducted in the past 30 years. PWV is the amount of water vapour in the atmosphere above a location given as if it was condensed to liquid precipitation [8]. PWV is a major source of opacity when observing at mm wavelengths and, thus, PWV levels need to be assessed at the potential sites before a mm-wave observatory can be built.

In this study, PWV measurements from the two sites in Namibia will be determined using different instruments: the AERONET sun photometer, ATMOSCOPE and H.E.S.S. meteorological data. To validate the literature value for the scale height of PWV, MERRA-2 data will be utilised. Furthermore, these PWV results will be compared to those obtained for the Swedish-ESO Submillimetre Telescope (SEST)[2] at the ESO La Silla observatory.

2. Instruments

In this study, only ground-based instruments will be used for the determination of PWV as satellite-based measurements typically have a coarse spatial resolution[3], which cannot properly take into account the topography of steep mountains of areas much smaller than 25 km^2, like Mt. Gamsberg. Similar limitations are known for the MERRA-2 re-analysis data, as reported in [5].

2.1 H.E.S.S. meteorological data

The H.E.S.S. telescopes record auxiliary data like meteorological quantities alongside the particle shower images. As per the usual length of an observing run, ambient temperature and

[1] https://www.mpi-hd.mpg.de/hfm/HESS

[2] https://www.eso.org/public/teles-instr/lasilla/swedish

[3] e.g., 5 km by 5 km, for the Moderate Resolution Imaging Spectroradiometer (MODIS, https://modis.gsfc.nasa.gov/about) aboard the *Terra* and *Aqua* satellites, see e.g. [9]

relative humidity data have been recorded every 28 minutes during cloud-free nighttime since 2003. The dataset analysed here ends in 2019. In this paper, "H.E.S.S." data shall refer to this auxiliary, meteorological data.

2.2 ATMOSCOPE meteorological data

The Autonomous Tool for Measuring Observatory Site COnditions PrEcisely (ATMOSCOPE), was developed by the Cherenkov Telescope Array (CTA)[4] community for site testing [10]. The measurements are integrated over a 1-minute interval, with atmospheric parameters such as pressure, ambient temperature, relative humidity, and cloud height being measured during this time. The data spans from 2013 through 2017.

2.3 NASA AERONET sun photometer

The AErosol RObotic NETwork (AERONET)[5] is a worldwide network of sun photometers. One of these is installed at the H.E.S.S. site. It measures PWV directly using a 940 nm filter and a 1.2° field of view. The AERONET PWV data were retrieved from the NASA database. The data is available at different processing levels: Level 1.0, Level 1.5, and Level 2.0, representing unscreened, cloud-screened, and quality-assured data, respectively. The instruments conduct the measurements every three minutes while tracking the Sun during day time and, for this study, data at processing level 2.0 from 02/2016–03/2021 were used.

3. Methods for calibration

While the AERONET directly[6] provides data products with PWV values, and the H.E.S.S. and ATMOSCOPE weather stations supply measurements of meteorological quantities. From those, the dew point temperature can be derived using the following expressions:

$$T_d = \frac{c\gamma_m(T,RH)}{b-\gamma_m(T,RH)}\,, \quad \text{with} \quad \gamma_m(T,RH) = \ln\left(\frac{RH}{100}\exp\left[\left(b-\frac{T}{d}\right)\left(\frac{T}{c+T}\right)\right]\right)\,, \tag{1}$$

where $b = 18.678$, $c = 257.14$°C, and $d = 234.5$°C are constants. Different empirical models to derive PWV values from atmospheric parameters were evaluated by [11]. They found that PWV derived from T_d yields the best performance with R^2 varying from 0.80–0.86 when correlated to contemporaneous AERONET PWV values. Following the same approach, we find $PWV\left(T_d^{\text{ATM}}\right) = (6.036 \pm 0.012)\exp\left((0.0723 \pm 0.0002)\,T_d^{\text{ATM}}\right)$, with $R^2 = 0.81$ between $PWV\left(T_d^{\text{ATM}}\right)$ from ATMOSCOPE and contemporaneous AERONET PWV.

As the direct AERONET measurements only coincide with the indirect measurements of the ATMOSCOPE (during daytime) but not with the measurements of the H.E.S.S. weather station (which only records data during cloud-free nighttime), a 3-step calibration process was adapted: firstly, from the meteorological data, the dew point temperature is inferred.

[4] https://www.cta-observatory.org

[5] https://aeronet.gsfc.nasa.gov

[6] Also this instrument makes use of indirect measurements of PWV through absorption strength at 940 nm and internal calibration procedures.

Then, the dew point temperature-derived PWV of the ATMOSCOPE, $PWV\left(T_d^{\mathrm{ATM}}\right)$, is calibrated with contemporaneous AERONET PWV measurements for the overlapping period from March 2016 to May 2017 with 43,886 data points (17% of ATMOSCOPE data) as depicted in Figure 1. Lastly, the dew point temperature of the H.E.S.S. weather station, $T_d^{\mathrm{H.E.S.S.}}$ is calibrated against simultaneous T_d^{ATM} so that PWV values can be inferred from the H.E.S.S. meteorological data, which covers the (by far) longest period of about 15 years.

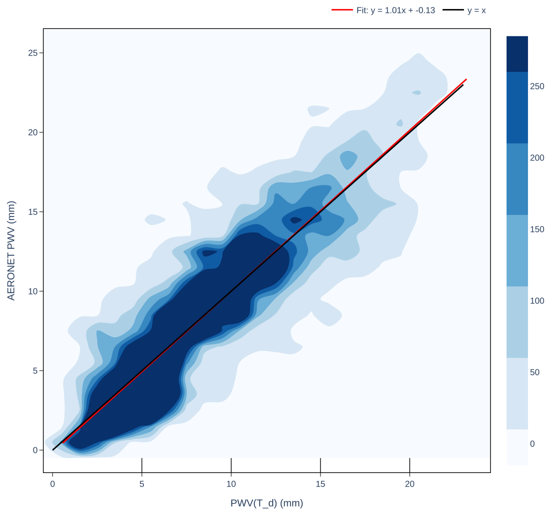

Figure 1: Correlation between AERONET PWV and derived PWV through dew point temperature over the H.E.S.S. site.

4. Results

4.1 Temporal behaviour of PWV at the H.E.S.S. site

The time series of the obtained PWV values for the H.E.S.S. site as well as their distribution including the median values are depicted in Figure 2. As expected, since the instruments measure PWV in different atmospheric conditions they present different values.

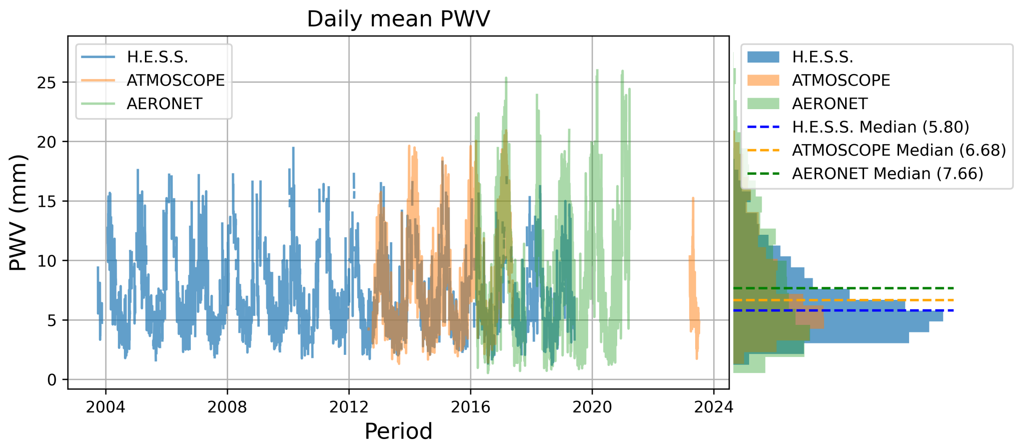

Figure 2: Time series and frequency distributions of the daily mean PWV as inferred from H.E.S.S. and ATMOSCOPE meteorological data and as measured by AERONET. The median values are 5.80 mm, 6.68 mm, and 7.66 mm, respectively. Note that these may be influenced by incomplete years.

Figure 3 shows the results for yearly folded time series with monthly and weekly averages. For each month/week, all available PWV data (for a given instrument) were averaged. The respective standard deviations are also depicted. The expected summer–winter seasonality is clearly visible.

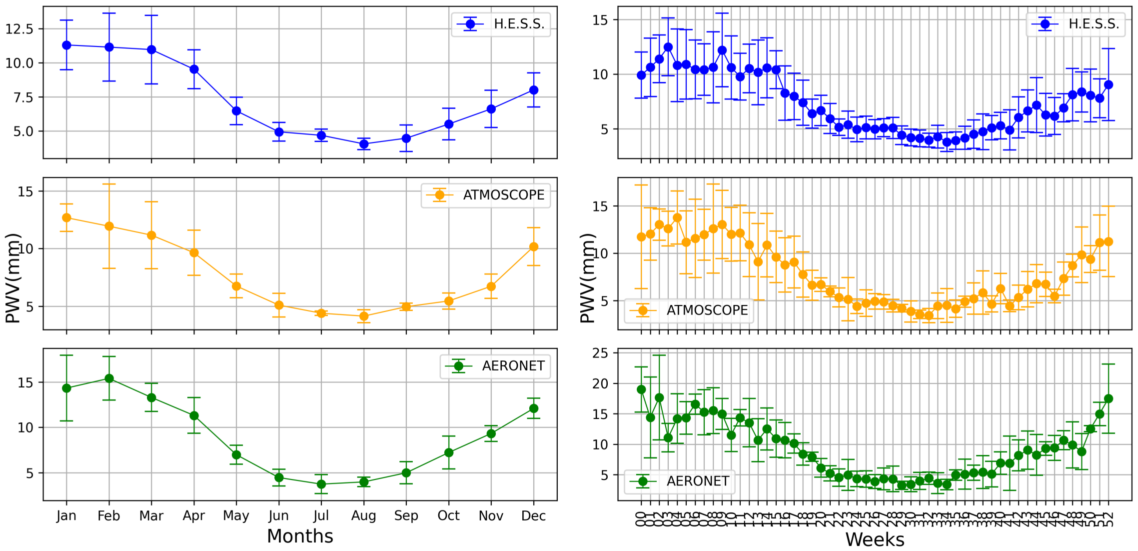

Figure 3: Yearly folded time series of the PWV as in Figure 2. Monthly (*left*) and weekly (*right*) averages and standard deviations are indicated. Connecting lines are depicted to guide the eye.

4.2 Data quality and biases in PWV measurements

When comparing PWV measurements, great care must be taken to only compare data taken under similar conditions. Analysing the day- and nighttime data of the ATMOSCOPE separately shows a difference of only 4% of the medians (6.74 mm / 6.47 mm). But crucially, the H.E.S.S. and AERONET data are (by construction) biased towards lower values, as the H.E.S.S. telescopes only record data during *cloud-free* nighttime and, AERONET, employing a sun photometer, also only records data during *cloud-free* daytime.

4.3 Scaling the results to the elevation of Mt. Gamsberg

All data presented up to here were recorded at the H.E.S.S. site at approximately 1,800 m a.s.l., about 30 km from Mt. Gamsberg. To estimate, the PWV atop Mt. Gamsberg at a height of 2,347 m a.s.l., we employ a scaling factor of $\exp\left({(1{,}800\,\mathrm{m} - 2{,}347\,\mathrm{m})}/{h_0}\right)$, with the scale height for PWV, $h_0 = 2{,}300$ m [12].

When testing this h_0 with MERRA-2 re-analysis data for the H.E.S.S. and Mt. Gamsberg sites over more than the past 23 years, the scaled $\mathrm{PWV}_{\mathrm{H.E.S.S.}}$ aligns with $\mathrm{PWV}_{\mathrm{Mt.\,G.}}$ at an $R^2 = 0.9$. More details can be found in [13].

4.4 Sites comparison

As the baseline plan for the AMT was to re-purpose SEST, we compare these results to the La Silla site, where SEST was operated at 2,400 m a.s.l. Besides measurements during the VLT site selection during the 1980s, also more recent, *cloud-free* GOES-8 satellite PWV data from 2000–2008 have been reported by ESO [14]. Figure 4 shows the weekly averages (over all years) and the standard deviation as well as the according distributions for La Silla, H.E.S.S., and scaled for Mt. Gamsberg.

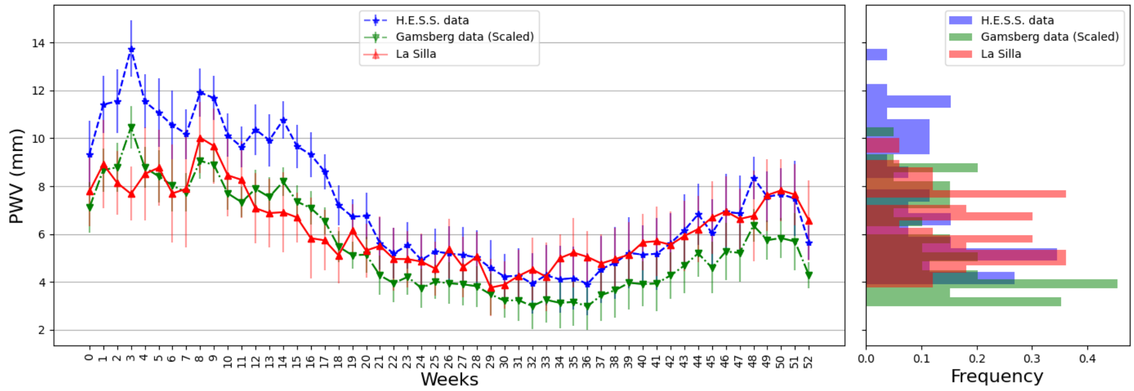

Figure 4: The weekly averaged PWV values with standard deviations as inferred for the H.E.S.S. site, scaled for Mt. Gamsberg, and reported for cloud-free times at La Silla in [14].

The preliminary findings of this study show that the H.E.S.S. site has a slightly higher yearly median PWV than the former site of the SEST telescope at La Silla, with Mt. Gamsberg reaching even lower numbers by scaling to its elevation. An overview is presented in Table 1.

Comparing our scaled results for Mt. Gamsberg with literature, a good agreement with in-situ measurements is observed [15]. Still, comparing with a recent study based on MERRA-2 re-analysis data [5], it becomes obvious that in-situ measurements on Mt. Gamsberg are crucial. While [5] state that their PWV estimates for the existing and candidate EHT sites generally match well with the literature, for Pico Veleta and JELM (Wyoming, US) they found differences of a factor of 2.

Table 1: Overview of the median PWV values for the H.E.S.S. site and Mt. Gamsberg obtained from (AERONET / ATMOSCOPE / H.E.S.S.) in this study, alongside literature values for Mt. Gamsberg and La Silla.

H.E.S.S. site	Mt. Gamsberg			La Silla
7.7 / 6.7 / 5.8 mm	6.1 / 5.3 / 4.6 mm	5.0 mm [15]	~ 9 mm [5]	6.0 mm [14]

5. Conclusion and outlook

As shown in subsection 4.3, the height difference of 547 m leads to 21% less PWV atop Mt. Gamsberg compared to the H.E.S.S. site. Still, as seen in subsection 4.4, the average amount of PWV at the H.E.S.S. site is comparable to La Silla for weeks 21 to 52, while being higher for the first 20 weeks of the year. The scaled values for Mt. Gamsberg are comparable to those of La Silla for the first 18 weeks, and are consistently lower than the La Silla ones from week 19, though within one standard deviation. One should note possible differences due to the different data sources (ground-based / satellite-based). More details of this study can be found in [13].

From this study and for comparison to the literature, it is clear that consistent measurements at both sites in Namibia are needed. For this, two identical Global Navigation Satellite System (GNSS) stations have been installed, one at each site. These data will form the basis of a forthcoming study.

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