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Humidity Measurements using Commercial Microwave Links

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1. Introduction

Atmospheric humidity strongly affects the economy of nature and has a cardinal part in a variety of environmental processes (e.g. Allan et al., 1999). As the most influential of greenhouse gases, it absorbs long-wave terrestrial radiation. Through the water vapour evaporation and recondensation cycle, it plays a central part in the Earth's energy redistribution mechanism by transferring heat energy from the surface to the atmosphere. Meteorological decision-support for weather forecasting is based on atmospheric model results, the accuracy of which is determined by the quality of its initial conditions or forcing data. Humidity, in particular, is a critical variable in the initialization of these models. The Mesoscale Alpine Programme (MAP) which set out to improve prediction of the regional weather, and specifically rainfall and flooding, concluded that accurate moisture fields for initialization were of great importance in achieving improved results (Ducrocq et al., 2002).

Humidity measurements are predominantly obtained by either surface stations, radiosondes or satellite systems. The typical surface station instruments commonly provide only very local, point, observations, and therefore suffer from low spatial resolution. Moisture though, is a field with an unusually high variability in the mesoscale as demonstrated, for instance, by structure functions (Lilly & Gal-Chen, 1983). Compounding this problem is the limited accessibility to position humidity gauges in heterogeneous terrain, or areas with complex topography. Satellites allow for a large area to be covered, but are frequently not accurate enough in measuring surface level moisture while this near-surface moisture is, in most cases, the important variable for convection. Radiosondes, which are typically launched only 2-4 times a day, also provide very limited information. Additionally, these monitoring methods are costly for implementation, deployment and maintenance.

Because of surface perturbation a point measurement close to the surface (for example 2m from the ground as in a standard meteorological surface station) is not satisfactory for model initialization. What is ideally required for meteorological modeling purposes is an area average measurement of near-surface moisture over a box with the scale of the model's grid and at an altitude of a few tens of meters. Current measuring tools cannot effectively provide this type of data. The method we present in this chapter provides a unique way of obtaining precisely this type of measurement. We introduce a technique, originally published by David et al. (2009), to measure atmospheric humidity using data collected by wireless communication networks.

2. Humidity monitoring using commercial microwave networks

2.1 Microwave links measurements as a basis for environmental monitoring

The propagation of the electromagnetic beam in the lower atmosphere, at centimeter and shorter wavelengths, is impaired by various weather phenomena (primarily precipitation, oxygen, water vapour, snow, mist and fog). The presence of line of sight and Fresnel zone clearance, propagation phenomena – diffraction, refraction, absorption and scattering – all affect the electromagnetic channel, causing attenuations to the radio signals (Raghavan, 2003). Thus, wireless communication networks provide built-in environmental monitoring tools, as was demonstrated for rainfall observations (Messer et al., 2006; Messer, 2007; Leijnse et al., 2007).

The attenuation of an electromagnetic wave, at requencies of tens of GHz, due to the interaction with rain droplets is well studied. The common approach relating the attenuation A [dB km^{-1}] with the rain rate R [mm $hour^{-1}$] is the power law model (Olsen at al., 1978):

$$A = aR^b \tag{1}$$

Where the constants a and b are, in general, functions of wave- frequency, its polarization and the drop size distribution (Jameson, 1991) . Given measurements of the Received Signal Level (RSL), the rain induced attenuation A can be estimated and in turn the average rainfall rate R.

Several works have shown that based on this technique, further applications, concerning rainfall monitoring, can be achieved (e.g. Zinevich et al., 2008-2009; Goldstein et al., 2009). Additionally, microwave links have been shown to be applicable for the identification of melting snow (Upton et al., 2007). An extensive study, concerning the hydrometeorological application of microwave links, was conducted, where in addition to the ability to measure precipitation, a Radio Wave Scintillometry-Energy Budget Method (RWS-EBM) to estimate areal evaporation using a microwave link (radio wave scintillometer) in combination with an energy budget constraint, was demonstrated (Leijnse, 2007). Zinevich et al. (2010) have recently discussed the prediction of rainfall measurement errors based on commercial wireless communication data.

2.2 Wireless communication networks as a water vapour monitoring system

Wireless communication, and in particular cellular networks, are widely distributed, operating in real time with minimum supervision, and therefore can be considered as continuous, high resolution humidity observation apparatus.

Environmental monitoring using data from wireless communication networks offers a completely new approach to quantifying ground level humidity. Since cellular networks already exist over large regions of the land, including complex topography such as steep slopes and since the method only requires standard data (saved by the communication system anyway), the costs are minimal.

Of the various wireless communication systems, we focus on the microwave point-to-point links which are used for backhaul communication in cellular networks, as they seem to have the most suitable properties for our purposes: they are static, line-of-sight links, built close to the ground, and operate in a frequency range of tens of GHz. Built-in facilities enable RSL measurements to be recorded at different time resolutions according to the different equipment types (typically, measurements are taken between once per minute to once per

24 hours). Some systems store only minimum and maximum RSL measurements per 15 minutes intervals. The magnitude resolution also varies for different types of equipment, it typically ranges between 0.1 dB to a few dB per link. Some of the microwave networks are equipped with automatic power control systems (however, not the ones used during the current study), in these cases, the transmitted signal level records should be taken into account in addition to the RSL measurements. In this research, the wireless system used for humidity observations has a magnitude resolution of 0.1 dB per link. This communication network provides attenuation data every few seconds, but only stores one data point per 24 hours (at 03:00 a.m.).The system can be configured to store data at shorter time intervals; it is a matter of technical definition by the cellular companies. Therefore, it has the potential of providing moisture observations at high temporal resolution. The length of an average microwave link is on the order of a few km and tends to be shorter in urban areas and longer in rural regions. In typical conditions of 1013 hPa pressure, 15 °C temperature and water vapour density of 7.5 g/m^3, the attenuation caused to a microwave beam interacting with the water vapour molecules at a frequency of ~ 22 GHz is roughly around 0.2 dB/km (Rec. ITU-R P.676-6, 2005, Liebe, 1985). Therefore, perturbations caused by humidity can be detected.

3. Theory and methods

At frequencies of tens of GHz, the main absorbing gases in the lower atmosphere are oxygen and water vapour. While oxygen has an absorption band around 60 GHz, water vapour has a resonance line at 22.235 GHz. The information concerning the attenuation and absorption by atmospheric water vapour and oxygen is based on the pioneering work of Van Vleck from 1947 (see also Gunn & East, 1954; Bean & Dutton, 1968). Although other atmospheric molecules have spectral lines in this frequency region, their expected strength is too small to affect propagation significantly (Raghavan, 2003; Meeks, 1976). As a consequence, an incident microwave signal, interacting with an H_2O molecule is attenuated, particularly if its frequency is close to the molecule's resonant one. Since backhaul links in cellular networks often operate around frequencies of 22 to 23 GHz, we focus on the 22.235 GHz absorbing line to monitor the water vapour.

3.1 The refractive index

In case of a homogeneous medium, the velocity of propagation, v, is given by (Raghavan, 2003):

$$v = (\varepsilon'\mu')^{-1/2} \tag{2}$$

ε' [Farads/m]- The permittivity of the medium through which the wave propagates.
μ' [Henries/m]- The magnetic inductive capacity of the medium.
In free space, the velocity of light, *c*, is known as follows:

$$c = (\varepsilon_0\mu_0)^{-1/2} \tag{3}$$

$\varepsilon_0 = 8.85\times10^{-12}$ [Farads/m]- The permittivity of free space.
$\mu_0 = 4\pi\times10^{-7}$ [Henries/m] - The magnetic inductive capacity of free space.
The dielectric constant of the medium, ε, which expresses the extent to which a material concentrates electric flux, is defined as the following ratio: $\varepsilon'/\varepsilon_0 = \varepsilon$.

$\mu'/\mu_0 = \mu$ - The magnetic permeability of the medium.
The refractive index of the medium, n, is defined as the ratio of the velocity in free space to that in the medium:

$$n \equiv \frac{c}{v} = (\varepsilon\mu)^{1/2} \tag{4}$$

Thus, for the propagation medium considered here, the value of μ can be taken as unity and therefore:

$$n^2 = \varepsilon \tag{5}$$

In our case, the dielectric is not perfect (due to absorption) and hence the refractive index $\tilde{n}$ is a complex quantity of which $n = \mathrm{Re}(\tilde{n})$ is the real part. The imaginary part, $\mathrm{Im}(\tilde{n})$, represents the absorption.

3.2 The absorption coefficient - γ

An electromagnetic wave propagating through a medium in the +z direction can be described as follows (Jackson, 1999):

$$\vec{E}(z,t) = E_0 e^{i(\tilde{k}z - \omega t)}\hat{\eta} \tag{6}$$

$$\vec{B}(z,t) = B_0 e^{i(\tilde{k}z - \omega t)}(\hat{z} \times \hat{\eta}) \tag{7}$$

The complex amplitudes of the electric field, $\vec{E}$, and the magnetic field , $\vec{B}$, are denoted by E_0 and B_0 , respectively.

$\hat{\eta}$ - Unit vector (in the x-y plane).

$\tilde{k}$ - The complex wave-number [rad/m].
ω - The angular frequency [rad/sec].
As the electromagnetic wave propagates, it carries energy along with it. The energy flux density (energy per unit area, per unit time) transported by the fields is given by the complex Poynting vector $\vec{S}$. The average in time, S_a, of the magnitude of the Poynting vector, is expressed as (Kerr, 1951; Raghavan, 2003):

$$S_a = \frac{1}{2}\mathrm{Re}(\vec{E} \times \vec{H}^*) \tag{8}$$

The asterisk signifies the complex conjugate while the vector $\vec{H}$, associated with the magnetic field $\vec{B}$, is given in equation (9):

$$\vec{B} = \mu'\vec{H} \tag{9}$$

The intensity, I, of an electromagnetic wave is proportional to S_a (Jackson, 1999). Therefore, by substituting equations (6), (7) and (9) into equation (8):

$$I(z) \propto \left| e^{i(\tilde{k}z - \omega t)} \right|^2 = e^{-2\mathrm{Im}(\tilde{k})z} \tag{10}$$

Hence:

$$I(z) = I_0 e^{-2\mathrm{Im}(\tilde{k})z} \tag{11}$$

Where I_0 and I are the intensity of the incident electromagnetic radiation and that after the material, respectively.
On the other hand, according to Beer-Lambert law:

$$I(z) = I_0 e^{-\gamma z} \tag{12}$$

While γ [m^{-1}] is the absorption coefficient.
Hence:

$$\gamma = 2\mathrm{Im}(\tilde{k}) \tag{13}$$

The connection between the complex refractive index and the complex wave number is known to be (Raghavan, 2003):

$$\tilde{n} = \mathrm{Re}(\tilde{n}) + i\mathrm{Im}(\tilde{n}) = \frac{c\tilde{k}}{\omega} = \frac{c\mathrm{Re}(\tilde{k})}{\omega} + i\frac{c\mathrm{Im}(\tilde{k})}{\omega} \tag{14}$$

Therefore, from equations (13) and (14):

$$\gamma = \frac{2\omega}{c}\mathrm{Im}(\tilde{n}) = \frac{4\pi f}{c}\mathrm{Im}(\tilde{n}) \tag{15}$$

Finally, in order to obtain γ in dB/km:

$$\begin{aligned} \gamma_{[dB/km]} &= \left[\frac{10}{\ln 10}\right]_{[dB]} \frac{4\pi\left[f_{[GHz]}\cdot 10^9\right]\cdot\left[N''_{[N\ units]}\cdot 10^{-6}\right]}{3\cdot 10^5_{[km/s]}} \\ &= 0.1820 f_{[GHz]} N''_{[N\ units]} \end{aligned} \tag{16}$$

While N'' is the imaginary part of the refractive index in N units (the index of refraction, n, is equivalent to (n-1)·106 N units).

3.3 Estimating humidity through wireless communication networks measurements

The attenuation γ [dB km^{-1}] due to dry air and water vapour is well studied and can be evaluated (Rec. ITU-R P.676-6, 2005, Liebe 1985) using:

$$\gamma = A_w + A_o \ [\mathrm{dB\ km^{-1}}] \tag{17}$$

Hence, according to equations (16) and (17):

$$A_W + A_O = 0.1820fN'' \quad [\text{dB km}^{-1}] \tag{18}$$

Where:
A_w: The specific attenuation due to water vapour [dB km^{-1}].
A_o: The specific attenuation due to dry air [dB km^{-1}]
Assuming moist air A_o, is one order of magnitude lower comparing to A_w, since at frequencies of ~22 GHz, the signal loss is caused predominantly by the water vapour (assuming no precipitation, fog or other hydrometeors found along the propagation path).
f: The link's frequency [GHz].
N''= N''(p,T,ρ): The imaginary part of the complex refractivity measured in N units, a function of the pressure p[hPa], temperature T[°C] and the water vapour density ρ[g m^{-3}].
While:

$$N'' = \sum_i S_i F_i + N''_D \tag{19}$$

Si= Si (p,T): The strength of the i-th line [KHz].
Fi= Fi (p,T,ρ,f): Line shape factor [GHz^{-1}].
N''_D= N''_D(p,T,f): The dry continuum due to pressure-induced nitrogen absorption and the Debye spectrum.
The summation is of the individual resonance lines from oxygen and water vapour, the sum extends over all lines up to 1000 GHz. The detailed expression of the functions of N'' is described in the literature (Rec. ITU-R P.676-6, 2005; Liebe, 1985).

3.4 Estimating humidity through surface station data

Since meteorological surface stations normally do not provide the absolute moisture ρ, it was derived using the known relations (Rec. ITU-R P.676-6, 2005; Liebe 1985; Bolton, 1980):

$$e_S = 6.112\exp\left(\frac{17.67T}{T + 243.5}\right) \tag{20}$$

$$e = \rho\frac{T + 273.15}{216.7} \tag{21}$$

$$\frac{e}{e_S}100\% \equiv RH \tag{22}$$

e_s- The saturation water vapour pressure [hPa].
e- The water vapour partial pressure [hPa].
T- The temperature [°C].
ρ- The water vapour density [g/m^3].
RH- The relative humidity [%].
Hence:

$$\rho = 1324.45 \times \frac{RH}{100\%} \times \frac{\exp\left(\frac{17.67T}{T + 243.5}\right)}{T + 273.15} \tag{23}$$

3.5 Statistical tests

We investigated the correlation between absolute humidity values calculated using the method described, and those measured using a regular humidity gauge. The correlation analysis was performed using the Pearson's correlation test with the level of significance at 0.05 (Neter, 1996).

The Root Mean Square Difference (RMSD) was used according to the following definition:

$$\text{RMSD}\ [g/m^3] = \sqrt{\frac{\sum_{i=1}^{N} (\rho_{mi} - \rho_{gi})^2}{N}} \tag{24}$$

ρ_{mi} - The i-th water vapour density measurement as measured using the microwave link [g/m³].

ρ_{gi} - The i-th water vapour density measurement as measured using the humidity gauge [g/m³].

N - Number of samples.

The humidity measurements taken via the microwave link were calculated from a signal instantaneously sampled at 03:00 a.m. Humidity measurements with the regular humidity gauge were taken at the surface stations every half hour, and from these measurements, the ones relating to the same hour were selected.

4. Results

Humidity observations, based on commercial microwave links data, were made in several different locations in Israel (Figure 1), and at several different times. The results presented here (Figure 2) are for Haifa Bay area, northern Israel and Ramla region, central Israel (four study cases are demonstrated here, two for each area). The observations of these four microwave links were made during November 2005, May 2008 and September 2007, April-May 2007, respectively.

Figures 2(a)-2(d) present the water vapour density ρ (g/m^3) as estimated using RSL measurements from the microwave link data (dark) vs. conventional humidity gauge data (bright).

The results, presented here, show very good match between the conventional technique and the novel method. The calculated correlation coefficients, in these cases, were between 0.82 to 0.9. The RMSD were found to be 1.8 [g/m^3] and 2 [g/m^3] for the links located by Harduf and Kfar Bialik, respectively. The RMSD of the central site measurements (Ramla area) were 3.4 [g/m^3] (for both cases in this region). Similar comparisons were performed for other links and other time slots showing correlations in the range of 0.5-0.9. The system from which the data were collected captures a single signal every 24 hours at 03:00 a.m. The surface station observations used were taken from the vicinity of the link's area at the same hour. Since rainfall causes additional signal-attenuation, days when showers occurred approximately at 03:00 a.m. till 04:00 a.m. (according to close by surface stations), were excluded.

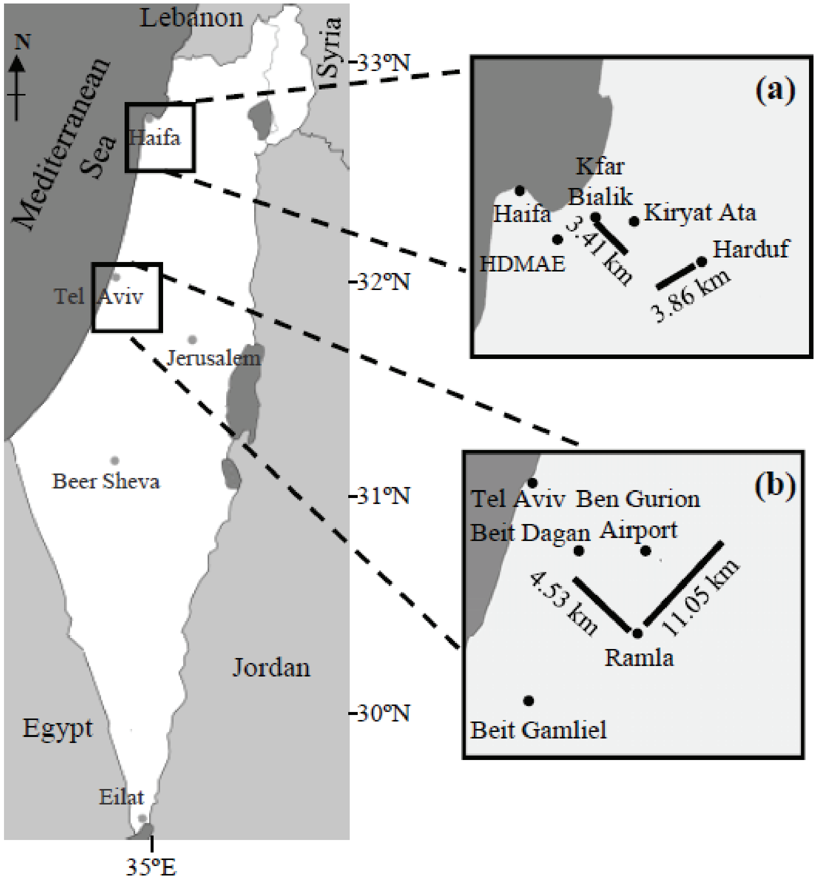

Fig. 1. The examined regions (taken from David et al., 2009).
1(a) North Israel: Two microwave links are presented (marked as lines) in front of Kiryat Ata, Haifa bay (where the humidity gauge is located). The first link (3.86 km long) is located on two hills, its transmiter and receiver are found at heights of 265 and 233 m Above Sea Level (ASL). The distance from the surface station to a point located in the middle of this wireless link is 7.5 km. The transmiting and receiving units of the second radio link (3.41 km) are situated 25 and 41 m ASL while the surface station- link distance is 3 km in this case. The Kiryat Ata surface station is situated 45 m ASL.
1(b) Central Israel: The two microwave links in front of Ben-Gurion airport meteorological station (humidity gauge's location). The distance from the surface station to a point located in the middle of the 4.53 km link is 6.5 km. This link's transmitter and receiver are located at heights of 95 and 63 m ASL. The longer link (11.05 km) is located 5 km from the surface satation while its transmitting and receiving units are situated 116 and 98 m ASL. The airport surface station is situated at 41 m ASL

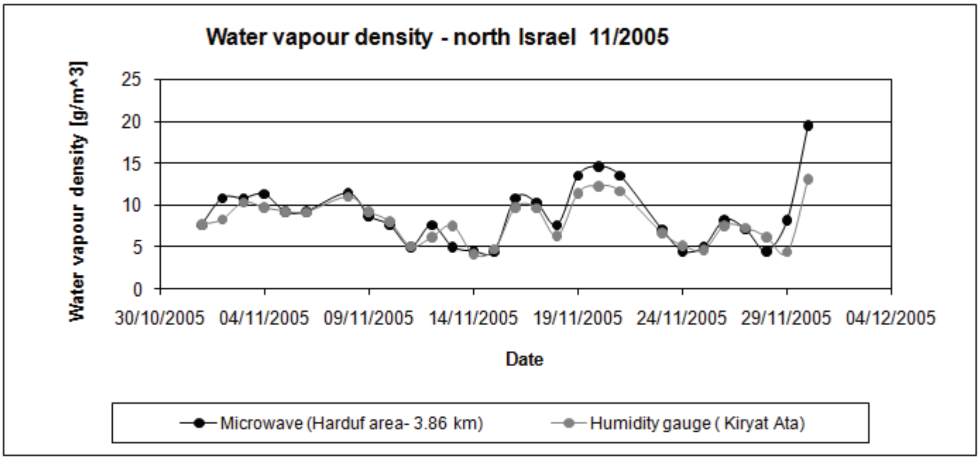

Fig. 2(a). Northern Israel (taken from David et al., 2009) - The observations were made, by the 3.86 km wireless link, during the month of November 2005, where 2 rainy days were excluded (7 and 22 November). The rainfall data were taken from two different surface stations situated in the Haifa District Municipal Association for the Environment (HDMAE) and in Kiryat Ata, about 12.5 km and 7 km, respectively, from Harduf (see Fig. 1a). The link's frequency is 22.725 GHz. The calculated correlation between the two curves is 0.9 while the RMSD is 1.8 [g/m^3]

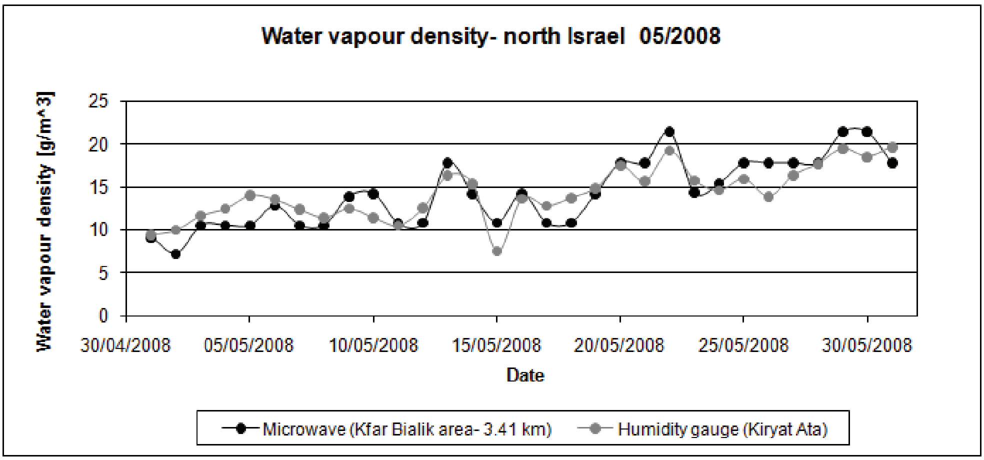

Fig. 2(b). Northern Israel - The humidity measurements were made, by the 3.41 km microwave link, during May 2008. The correlation between the two measurements is 0.87 with RMSD of 2 [g/m^3]. Link's frequency: 22.05 GHz

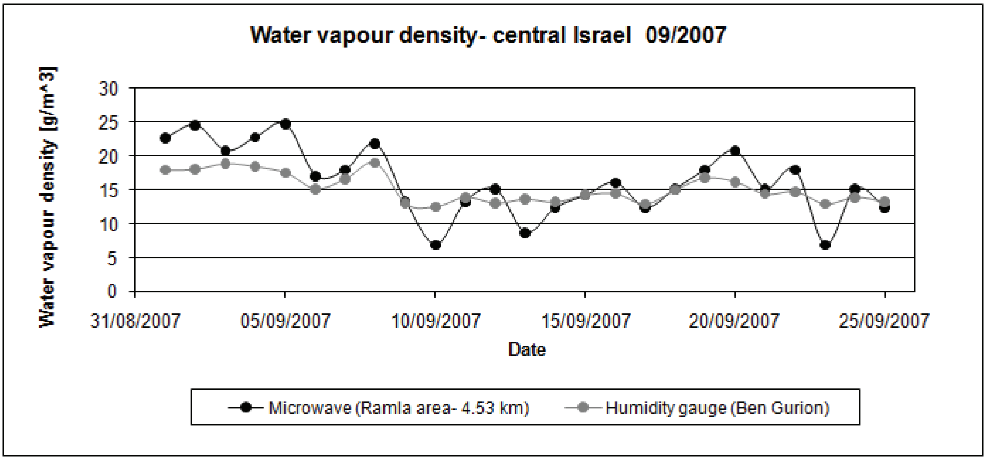

Fig. 2(c). Central Israel - The measurements were taken during the month of September 2007 (25 days). The link's frequency is 22.525 GHz and the calculated correlation between the time series is 0.89 with RMSD of 3.4 [g/m^3]

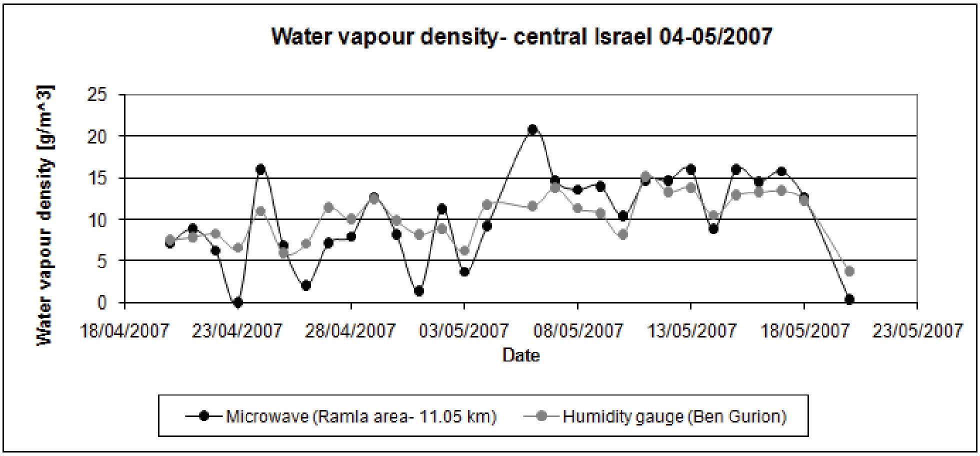

Fig. 2(d). Central Israel (taken from David et al., 2009) - The measurements were taken between 20 April and 20 May 2007, excluding 2 days when showers occurred (5 and 19 May). The precipitation data were taken from Beit Gamliel surface station which is located about 13 km from Ramla (see Fig. 1b). It should be noted that it is possible that the increased attenuation in this case that is greater than the typical moist air attenuation, was caused as a result of other interference such as wind moving the transmitter or receiver (Leijnse et al., 2007). As there was a surface station that recorded precipitation in the area, the increased attenuation was ascribed to precipitation. Further investigation is required to identify the sources of these perturbations. The link's frequency is 21.325 GHz and the calculated correlation between the time series is 0.82 with RMSD of 3.4 [g/m^3]

The largest difference between the traditional and the novel measurement methods (Figure 2d) appears on the night of 6 May 2007. This night was a holiday in Israel ("Lag Ba'omer"), where hundreds of bonfires were lit all across the country. As a result, many particles were released into the low atmosphere speeding up the creation of smog and possibly fog (the measured relative humidity by a radiosonde launched at 03:00 a.m. from Beit Dagan (Fig. 1b), a few km away from the microwave link, at an altitude of 95 m ASL was 97%). The reason for the additional attenuation observed by the microwave link (expressed by a higher moisture level) might be due to local fog (Raghavan, 2003), implying that the system may provide the ability to monitor this phenomenon through the use of wireless communication data. When excluding the 6 May measurement, the correlation increases to 0.85 and the RMSD decreases to 2.9 [g/m^3]. Further investigation is needed concerning this point.

5. Uncertainties

Commercial microwave links are designed for efficient data transmission and high communication performance rather than measuring the water vapour density. Hence, estimation of the uncertainties for observations that are non-optimal in the first place is fundamental in order to assure usability of the data. The uncertainty in measuring temperature and pressure are of the magnitude 0.1 degrees Celsius, and 1 mb, respectively. However, changes of this magnitude in pressure or temperature do not create a significant change in the absolute humidity calculation based on this model (Rec. ITU-R P.676-6, 2005; Liebe, 1985). The dominant uncertainty affecting the absolute humidity calculation is that of the attenuation quantization error. The uncertainty depends on the path length. Since the quantization error of the wireless system used is 0.1 dB per link, the uncertainty in evaluating attenuation is ± 0.025 dB/km for a typical 4 km long link (a length which is of the order of magnitude of three out of the four links used in the cases presented here). As a result we get that the error in calculating absolute humidity for this link length is of the magnitude of ± 1 g/m^3. In the case of an 11.05 km link, the uncertainty in evaluating the attenuation is ± 0.01 dB/km, hence the corresponding error in calculating the absolute humidity is of the magnitude of ± 0.5 g/m^3. The estimated uncertainty in measuring humidity with regular humidity gauges is about 0.2 to 0.5 g/m^3 (depending on the relative humidity and the temperature), while the error in measuring relative humidity was taken to be 3%.

Dry air effect on attenuation is one order of magnitude lower than that of water vapour in this case. Quantitatively it is about 0.01 dB/km for dry air and 0.19 dB/km as a result of humidity (for a 1 km link, operating near 22 GHz, temperature of 15 °C, humidity of 7.5 g/m^3 and a sea level pressure). However, the algorithm takes into account the effects of dry air, and corrects for them. Another atmospheric parameter which can be estimated based on the model is the imaginary part of the refractive index- N'', as aforementioned, this variable represents the absorption. Under the same atmospheric conditions as mentioned previously and for a link operating near 22 GHz, a typical value which was obtained for this variable, based on the model, is: 0.044 [N units] while the uncertainty is ± 0.006 [N units] for a 4 km link and ± 0.003 [N units] for an 11 km link.

Rain, fog, snow and clouds create additional attenuation in relation to that caused by water vapour. One of the research challenges we are faced with is separating the effects of different attenuation sources. As we aim to prove feasibility, at this stage, the technique is limited to periods where none of the aforementioned phenomena exist along the link line-of-sight. The microwave links are sensitive to mechanical oscillations. Therefore, strong winds, that may cause movement of either the receiver or the transmitter (or both), may also be considered as a source of error (Leijnse et al., 2007).

6. Conclusions and future plan

Our results show very good agreement between the conventional way to measure water vapour over the low troposphere and our proposed, novel method based on wireless communication networks measurements. However, some disparities are expected of course. That is since measurements from the microwave links are line integrated data, where in-situ measurements as made by a typical humidity gauge are point measurements. In addition, the difference in location between the measurement sites and particularly the difference in the moisture level with altitude which can be significant at night hours, introduces additional disparities between the microwave measurements and those made by the conventional humidity gauges.

The measurements from the northern links present a better correspondence with the humidity gauge readings, compared to the measurements which were made by the microwave links located in central Israel. Additionally, it is possible to note that the Harduf area link presents, in general, a better agreement with the humidity gauge data as compared to that of the other three links. While it will need to be further investigated, we can suggest several reasons for the observed discrepancy: The representativeness of the spot humidity gauges is a factor. It is possible that the humidity gauge in the northern area better represents the average humidity in the region than the Ben Gurion airport humidity gauge does. Thus, it is possible that, the measurements of the central area humidity gauge do not correspond as well to the measurements of the microwave link that represent the average humidity along the paths (distances of 4.5 km and 11.05 km). Moreover, it is important to note that the transmitting and receiving units of the Harduf link are located on hilltops, and are higher off the ground, so that the microwave beam travels over a valley. On the other hand, while the other three links are located between 25 to 95 m ASL, their masts heights (where the transmitters and receivers are installed) are only between 15 to 33 m above the surface itself. It is possible then, that those links are more prone to reflection and surface interference (Leijnse et al., 2007).

The wireless measurement technique can thus either replace existing techniques or preferably be used in conjunction with them in order to obtain more accurate moisture fields.

Given the newly available data provided by the wireless communication facilities, improved initialization of atmospheric models can be achieved, thus enhancing prediction and hazards warning skills as well as providing a better understanding of the global climate system.

7. Acknowledgements

We wish to acknowledge and thank Y. Dagan, Y. Eisenberg (Cellcom), N. Dvela, A. Shilo (Pelephone) for their cooperation and for providing the microwave data for our research.

We also thank B. Goldman (Haifa District Municipal Association for the Environment) and A. Arie (Meteo-tech) for humidity gauge data.

In addition, we would like to thank our research team members: A. Zinevich, Y. Ostromtzky, Dr. R. Samuels, D. Charkasky, O. Auslender and R. Radian (Tel Aviv University) for their advice and assistance throughout this research.
This work was supported by a grant from the Yeshaya Horowitz Association, Jerusalem.
Additional support was given by the PROCEMA-BMBF project and by the GLOWA-JR BMBF project.

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