Water vapor, fog and rainfall monitoring using commercial microwave network measurements

By

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In memory of my dear father Moshe David z”l (1938-2011)

As a young adult, my father came to Israel in its early days as an independent nation. Although he was an excellent pupil at school, due to the economic constraints of the times, he was not able to continue to advanced academic studies as he would have liked. In time he made a living for himself, met my mother – Yafa, and started our family, which he supported with great love and unparalleled dedication throughout the years. He always stressed to us, his children- Shay, Maya and I the importance of intellectual development, advancement and education.

Finishing this work completes this circle and is a fulfillment of a personal dream for me and for him, as his son. It is with great honor that I dedicate my work to his memory.
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ABSTRACT

Weather conditions and atmospheric phenomena affect the wireless electromagnetic channel, causing attenuations to the radio signals. Thus, wireless communication networks are in effect built-in environmental monitoring facilities. In particular, wireless microwave links, most sensitive to atmospheric hydrometeors, are widely deployed by cellular providers for backhaul communication between base stations, a few tens of meters above ground level. As a result, microwave networks measurements have the potential to provide near-surface observations with high spatial and temporal resolution. Further, the implementation cost is minimal, since the microwave data used are already collected and saved by the cellular operators. In addition – many of these links are installed in areas where access is difficult, for instance, in regions of complex topography or within the urban canopy. As such, the proposed technique enables measurements in places that have been hard to measure in the past, or have never been measured before.

The research presented in this work is divided into three parts, while each part is focused on monitoring a specific atmospheric phenomenon.

The goal of the first part is to show the feasibility for fog identification and intensity estimation. A method is proposed and is demonstrated by two cases of heavy fog that took place in Israel. During these events, fog covered wide areas (tens of kilometers) and caused severe decrease in visibility, dropping as low as several tens of meters. Liquid water content and visibility values were estimated using measurements from tens of microwave links deployed in the observed area for each event. The values were found to be in the range of 0.5-0.8 gr/m³ – high concentration values that match the maximum value range observed in field measurements carried out for prior studies in different test areas in the world. The visibility ranges calculated, between 30 and 70 meters, fit the visibility assessments from the specialized measuring means operating in the observed area at the same time.

A second part of the research shows the potential found in these networks to provide humidity measurements. The work presents real-data measurements taken from microwave links used in a backhaul cellular network that show convincing correlation to surface station humidity measurements. The measurements were taken daily in two
sites, one in northern Israel, and the other in the center of it. The correlation between the microwave link measurements and the humidity gauges ranged between 0.9 and 0.82 for both sites with Root Mean Square Differences (RMSD) ranging between 1.8 (g/m$^3$) and 3.4 (g/m$^3$).

Monitoring of precipitation and in particular sudden rain, in rural dry climate regions, is a subject of great significance in several weather related processes such as soil erosion, flash flooding, triggering epidemics and more. The rainfall monitoring facilities in these regions and as a result precipitation data are, however, often, severely lacking. Cellular networks infrastructure are often being situated in dry areas, covering large parts of these climatic zones. The goal of the 3$^{rd}$ part of the research is to show the potential found in these already existing systems to provide early monitoring and essential precipitation information, directly from arid regions, based on standard measurements of commercial microwave links. This potential is exemplified here over the Negev and Judean deserts, located in South and Eastern Israel. Results of two different rainfall events that occurred in these regions are presented. It is shown that the microwave system measured precipitation between at least 50 minutes (in case 1) and at least 1 hour and 40 minutes (in case 2) before each of the sparse rain gauges. During each case, the radar system, located relatively far from the arid sites, provided measurements from heights of at least 1500 m and 2000 m above surface, respectively, and therefore, may not be well representative of the actual near surface rainfall. A third case study demonstrates the relative advantage of microwave links to measure precipitation intensity in respect to the radar system, over an area of complex topography located in northeastern Israel, relatively far (~150 km) from the radar.

The results presented in this work point to the strong potential of the proposed methodologies to provide the essential meteorological information. Transforming the concepts into practical applications requires additional examination and further research.
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ABBREVIATIONS

AMS.................................................American Meteorological Society
ATPC..............................................Automatic Transmit Power Control
CI..................................................Convection Initiation
dB....................................................................Decibel
DSD..................................................Drop Size Distribution
FSSP..................................................Forward Scattering Spectrometer Probe
IMS..................................................Israel Meteorological Service
IWV..................................................Integrated Water Vapor
ILW..................................................Integrated Liquid Water
ITU..................................................International Telecommunication Union
LT..................................................Local Time
LWC..................................................Liquid Water Content
MAP..................................................Mesoscale Alpine Programme
Med..................................................Median
MLs..................................................Microwave Links
MOR..................................................Meteorological Optical Range
MSG..................................................Meteosat Second Generation
PDH..................................................Plesiochronous Digital Hierarchy
PVM..................................................Particle Volume Monitor
QPE..................................................Quantitative Precipitation Estimates
RH..................................................Relative Humidity
RMSD...............................................Root Mean Square Difference
RSL..................................................Received Signal Level
RVR..................................................Runway Visual Range
SDH..................................................Synchronous Digital Hierarchy
UTC..................................................Universal Time Coordinated
WVR..................................................Water Vapor Radiometers
WMO..................................................World Meteorological Organization
**List of Symbols**

\(a\) ................................................................. Fog droplet radius

\(a_m\) ........................................ Amplitude of the field distribution due to the magnetic multipoles

\(\hat{a}\) .................................................. Estimated fog induced attenuation

\(A_o\) .................................................. Attenuation due to dry air

\(A_f\) .................................................. Fog induced attenuation

\(A_{M, \gamma}\) ........................................ Measured attenuation

\(A_p\) .................................................. Precipitation induced attenuation

\(A_v\) .................................................. Water vapor attenuation

\(A_w\) .................................................. Wet antenna attenuation

\(\hat{A}_w\) ........................................ Estimated wet antenna attenuation

\(b, a\) .................................................. Rainfall power law coefficients

\(b_m\) ........................................ Amplitude of the field distribution due to the electric multipoles

\(\bar{B}\) .................................................. The magnetic field

\(c\) .................................................. Light velocity

\(D\) .................................................. The equivalent rainfall drop diameter

\(\bar{E}\) .................................................. The electric field

\(e\) .................................................. Water vapor partial pressure

\(e_s\) .................................................. Saturation water vapor pressure

\(f\) .................................................. Link frequency

\(F\) .................................................. Absorption line shape factor

\(I\) .................................................. Electromagnetic radiation intensity

\(k\) .................................................. The complex wave-number

\(L\) .................................................. Link length

\(\bar{L}\) .................................................. Average links length

\(\tilde{n}\) .................................................. Complex refractive index

\(N_d\) .................................. Drop Size Distribution (DSD) for equivalent rain drop diameter

\(N''\) ........................................ The imaginary part of the complex refractivity in N units

\(N''_D\) ........................................ The dry continuum

\(N_D\) ........................................ Droplet number concentration

\(p\) .................................................. Barometric pressure
Incident power

\( Q(a, \lambda) \)  

Total cross section

\( Q_a \)  

Absorption cross section

\( Q_d \)  

Extinction cross section (at a given frequency and polarization)

\( Q_s \)  

Scattering cross section

\( R_L, R \)  

Path averaged rainfall intensity

\( \hat{R} \)  

Estimated path average rain rate

\( \hat{s} \)  

The energy flux density

\( S_a \)  

Time average of the magnitude of the energy flux density

\( S_i \)  

The \( i \)-th absorption line strength

\( t \)  

Time component

\( T \)  

Temperature

\( V \)  

Visibility

\( V_d \)  

Raindrop terminal velocity

\( x \)  

Mie size parameter

\( z, s \)  

Spatial location along the propagation path

\( \alpha, \beta \)  

Wet antenna coefficients

\( \beta \)  

Permittivity dependent function

\( \hat{\gamma} \)  

Estimated path integrated attenuation induced by fog

\( \Gamma \)  

Absorption coefficient

\( \varepsilon \)  

Permittivity of the medium

\( \varepsilon_r \)  

Dielectric constant of the medium

\( \hat{\eta} \)  

Unit vector (in the x-y plane)

\( \lambda \)  

Radiation wavelength

\( \mu \)  

Magnetic permeability of the medium

\( \mu' \)  

Magnetic inductive capacity of the medium

\( \nu \)  

Wave propagation velocity

\( \rho \)  

Water vapor density

\( \rho_s \)  

Water vapor density measured using a humidity gauge

\( \rho_m \)  

Water vapor density measured using a microwave link

\( \rho_w \)  

Density of liquid water
Φ ........................................ Frequency and temperature fog dependent coefficient

ψ .................................................. Total atmosphere induced attenuation

ω ...................................................... The angular frequency

[ ]q, Δq .................................................... Digital quantization error
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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

Accurate measurements of hydrometeors at the Earth’s surface are required for meteorological analysis and forecasting, hazard warning, climate studies, and for various applications in hydrology, agriculture, aeronautical services and environmental studies (WMO, 2008). However, the accuracy of existing instruments is often limited as a result of technical and practical constraints. Existing techniques including satellite systems and ground level measuring means—often suffer from low spatial resolution, high cost or lack of precision when measuring near the surface (e.g. Ellrod, 1995; WMO, 2008). At frequencies of tens of GHz, various atmospheric hydrometeors: precipitation, water vapor, sleet, mist and fog affect microwave beams, causing perturbations to radio signals (Rec. ITU-R P.838-2, 2004; Rec. ITU-R P.676-6, 2005; Rec. ITU-R P.840-4, 2009), as depicted in Fig. 1:

![Transmission losses at millimeter waves resulting from different atmospheric phenomena.](image-url)

Fig. 1 Transmission losses at millimeter waves resulting from different atmospheric phenomena.
Hence, microwave radiation based techniques to sense the environment are widely used and employed. Predominant weather phenomenon causing attenuation to the microwave signals is rainfall. As reviewed by Zinevich (2010), the MANTISSA project (Capsoni et al. 2004) has been utilizing dual-frequency links, at different, specifically selected frequencies to produce estimates of path-averaged rain (Holt et al. 2000; Rahimi et al. 2003) as well as rainfall spatio-temporal distribution, when combined with rain gauge and radar data (Grum et al. 2005). The use of dual-frequency links allows the Quantitative Precipitation Estimate (QPE) to be made as a linear function of the ratio of two attenuations, thus lowering the effect of unknown Drop Size Distribution (DSD) and producing reliable estimates. The advantage of MLs over conventional rain gauges for high temporal resolution measurement has been shown (Minda and Nakamura, 2005) as well as calibration and correction of radar system data using input from microwave link systems (Krämer et al., 2005; Rahimi et al., 2006). Estimation of DSD based on dual wavelength measurements of path averaged microwave attenuation, has also been shown (Rincon and Lang, 2002).

Part of the research has also investigated the potential for monitoring other-than-rain phenomena using measurements from MLs. These works include: identification of melting snow (Upton et al., 2007), measuring the absolute humidity based on propagation phase delays (Chwala et al., 2013) and estimating the areal evaporation utilizing a ML in combination with an energy budget constraint (Leijnse et al., 2007a).

However, utilization of MLs that are optimized for environmental monitoring requires dedicated installation procedures and expensive equipment. Thus, the usage of these instruments in practice is limited and not wide spread.

On the other hand, recently, it has been recognized that commercial microwave communication networks can be used as a built in environmental monitoring facility, this ability was first demonstrated for rainfall observations (Messer et al. 2006; Leijnse et al., 2007b). The wireless MLs used in these networks, are widely deployed by cellular providers for backhaul communication between base stations. Typically, these systems operate at frequencies between 6 to 40 GHz and installed at heights of only a few tens of meters off the surface and, they are widely spread across the terrain and provide real time and continuous measurements at high temporal resolution with

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3 Microwave Attenuation as a New Tool for Improving Storm-water Supervision Administration
minimum supervision. Receiving equipment typically measures the Received Signal Level (RSL) that can be utilized to estimate the weather related induced attenuation. Finally, the implementation costs are minimal since the requested data are standard data collected and logged routinely by the communication providers.

The use of existing communication links for atmospheric monitoring has its own set of built in challenges and limitations, due to the system being optimally designed for communication and data transfer needs rather than atmospheric observation needs. Therefore, in these cases the system's operating frequency, signal polarization and the geometric spatial deployment of the MLs are already set. The systems provide measurements at predetermined temporal resolution (typically in the range of between one sample per minute down to one sample per day). Some systems provide maximum and minimum RSL measurements over a given time interval, while others provide an instant measurement.

Rainfall monitoring, using commercial MLs, has been studied over the past few years. These links have been shown to be useful for identifying dry and rainy periods (Hadar, 2009; Chwala et al., 2012; Rayitsfeld et al.2012; Wang et al., 2012) and for estimating path averaged rain rates (e.g. Messer et al., 2006; Leijnse et al., 2007b, 2008; Zinevich et al., 2010). Reconstruction of rainfall intensity distribution using commercial microwave networks has also been presented (e.g. Messer, 2007; Goldshtein et al., 2009; Zinevich et al., 2008, 2009; Overeem et al., 2013). Recently, a novel technique to classify precipitation type as rainfall or sleet has been shown (Cherkassky et al., 2012, 2013). Notably, most of the work done in this field of research till today was focused on the ability to estimate and detect rainfall (Messer and Sendik, 2013). However, commercial microwave networks seem to have suitable properties and the potential to monitor also other-than-rain phenomena with certain potential advantages over existing monitoring tools.

In this work feasibility studies are presented, demonstrating the potential for monitoring of the atmospheric water vapor (David et al., 2009, 2011) and dense fog (David et al., 2012a, 2013a) based on existing RSL measurements from commercial microwave communication networks. An additional part of the research demonstrates the potential found in these already existing systems to provide advantageous rainfall observations from dry climate- prone to floods regions and areas of complex terrain (David et al., 2013b).
Let me briefly discuss the different atmospheric phenomena I focus on in this work and the instruments most typically used to monitor these parameters.

### 1.1.1 Fog

Fog is defined as water droplets suspended in the atmosphere, near the surface of earth that reduce visibility to less than 1 km (AMS, 2000). According to the World Meteorological Organization (WMO), visibility is defined as the greatest distance in a given direction at which it is possible to see and identify a prominent black object against the sky at the horizon in the daylight, or could be seen and recognized during night if the general illumination were raised to the level of normal daylight (WMO, 2008). Fog is predominantly created as a result of humid air being cooled to the point of saturation where it can no longer contain water vapor in gaseous phase alone (dew point temperature). Generally, fog can be divided into two main types according to two predominant ways of formation. Radiation fog is created when the air temperature over a land mass is reduced as a result of radiational cooling. Advection fog is caused when an air parcel is transported (or "advected") over a relatively cold surface (Gultepe et al., 2007). The impact of fog on human beings and on the environment is considerable. Fog harvesting, for instance, can produce fresh water for gardening, afforestation and even potable water that may have a significant contribution particularly in water scarce regions (Oliver, 2004; Klemm et al., 2012). It was observed that fog is important for seeder-feeder orographic precipitation enhancement (e.g. Wilson and Barros, 2013). Moreover, in forest ecosystems, fog takes a cardinal part in the water balance of these natural environments (e.g. Dawson, 1998; Wrzesinsky and Klemm, 2000). An important role fog plays in cleaning the atmosphere through the process of particle scavenging and then drop deposition has also been shown (Herckes et al., 2007). On the other hand, air pollutants that exist in the atmosphere can interact and dissolve in the condensed water droplets creating smog (a portmanteau of smoke and fog) that may harm human health, adversely affect plants and damage structures (e.g. Wichmann et al., 1989; Dam and Hoang, 2008). Information concerning the Liquid Water Content (LWC) of fog makes it possible to define the concentration of air pollutants through analysis of fog droplet samples (e.g. Tago et al., 2006). However, the central negative effect attributed to fog, is reduced visibility that can lead to heavy financial damages, grave accidents and loss of life.
(Croft et al., 1995; Pagowski et al., 2004). The total economic impact of the presence of fog on aviation, marine and land transportation can reasonably be compared to the impact of tornadoes or, in some cases, even those of hurricanes (Gultepe et al, 2007). Furthermore, it has been recently shown that while the number of road accidents due to rain has declined considerably, the totals in foggy conditions have not changed significantly (Pisano et al., 2008).

Existing means of measuring fog provide reliable measurements in most cases, but are limited in the spatial range they can cover, in their availability, and by their high implementation costs. Predominant techniques for detection of fog and measuring visibility include: trained human observers, transmissometers, satellites and instruments that measure the scatter coefficient. A trained human observer assesses visibility by the appearance or occlusion of objects at known distances from the observer's present location. However, this assessment is a subjective judgment by a particular observer, one observer's estimation might disagree with another's when assessing the same visibility conditions. One of the most common instruments for measuring the light extinction coefficient is the transmissometer (WMO, 2008). Transmissometers include a light source, such as a laser, and a detector for detecting either light from the light source directly or light from the light source that is reflected back to the detector from a reflector such as a mirror. The source emits a modulated flux of light with constant mean power while the receiving unit contains a photodetector to measure the light falling on it. This instrument measures the mean light extinction coefficient in a horizontal cylinder of air between the source and the receiver that can be located from a few meters to several hundreds of meters apart.

Although this device is considered very accurate, its cost is extremely high. An additional technique includes instruments measuring the scatter coefficient. Both scattering and absorption contribute to the atmospheric attenuation of light. The main contributor to reduced visibility is the scatter phenomena created by the water droplets, while the absorption factor is, in general, negligible. This being the case, measuring the scatter coefficient may be considered as equal to measuring the extinction coefficient. By concentrating a beam of light on a small volume of air, the proportion of light being scattered in sufficiently large angles and in non-critical directions can be determined through photometric means (WMO, 2008). However, this technique only allows for a small sample volume to be measured. As a result, the
visibility representativeness obtained is limited. Satellites have the advantage of providing large spatial coverage. Nevertheless, in some cases, they struggle to supply fog detections at ground level. High or middle altitude clouds along the line of sight between the ground and the system may obscure ground level fog (e.g. Ellrod, 1995). It is also difficult to differentiate, using this technique, whether the observation reflects actual fog, or low stratus clouds, found at higher levels off the surface. In order to improve the fog detection algorithms additional spectral channels are needed (Ellrod and Gultepe, 2007).

Some instruments were designed to provide measurements of the fog LWC (Gerber, 1984; Arends et al., 1992; Emert, 2001; Schwarzenboeck et al., 2009). While all are spatially limited, commonly used tools include the Particle Volume Monitor (PVM), Forward Scattering Spectrometer Probe (FSSP) and hot-wire probes. The PVM is based on the principle of forward scattering of light and supplies information concerning the LWC and total particle surface area. The FSSP is designed to provide measurements of the droplet size distribution and based on this information the LWC can be derived. Hot-wire probes, mostly used on aircrafts, measure LWC by monitoring the energy required to evaporate collected fog-droplets using inertial impaction and interception on a heated cylinder.

1.1.2 Water vapor

In a system of moist air, the absolute humidity is defined as the ratio of the present water vapor mass to the volume occupied by the mixture (AMS, 2000), i.e. the density of the water vapor component. Relative Humidity (RH) is defined as the percent ratio of observed vapor pressure to the saturation vapor pressure of water at the same temperature and pressure (AMS, 2008). 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 vapor 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.

Fabri (2006) reviews the measurable need in sufficient monitoring of water vapor: Despite the ongoing improvement in observation and modeling tools, forecasting precipitation during the warm season is still a considerable challenge. The lower success of forecasting in summer (Uccellini et al. 1999) is related to the fact that warm season rainfall has a more convective nature, and thus, greatly depends on the mesoscale variability of dynamical and thermodynamic fields. These, unfortunately, are inadequately observed and water vapor is one of the least well measured of these variables. As a result, prediction of convective precipitation, on the storm scale, is limited because of the uncertainty of water vapor distribution in the atmosphere and the amount of water in the soil (National Research Council, 1998). The available tools for observing kinematics at the mesoscale (e.g. radar) have been considerably better than those for observing thermodynamic parameters (mostly in situ sensors). As a result, field studies of convection initiation (CI) have focused on dynamic issues, such as the importance of convergence boundaries (Wilson and Schreiber 1986) and the dryline in particular (Rhea 1966; Segal et al., 1994), while the work investigating the potential role of humidity and temperature on CI, and the resulting strength of precipitation, though significant, is mostly based on numerical experiments (Lee et al. 1991; Crook 1996) or statistics gathered from synoptic information (Zawadzki et al. 1981). To address the issues associated with time domain change in the 3D distribution of water vapor and its impact on understanding and predicting warm-season precipitation events, the International H$_2$O Project (IHOP$_{2002}$) was put together (Weckwerth et al. 2004). IHOP$_{2002}$ had four research components: Quantitative precipitation forecasting, atmospheric boundary layer, instrumentation and CI. Despite the focus of the experiment on H$_2$O, the CI work in IHOP$_{2002}$ emphasized dynamical forcing (variability in the lifting depth and the creation of secondary circulations near convergence lines, or mesoscale boundaries) and kinematic controls (e.g. the kinematic effects of drylines and outflows, boundary inflections, and vortices). The effect of moisture controls on CI received relatively little attention in comparison. A key reason is the difficulty in measuring the humidity field. 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). Moisture (and temperature) are
more poorly characterized than wind or even precipitation, and so questions such as the magnitude of small-scale variability of moisture in the boundary layer, and its effect on CI (e.g. Weckwerth et al. 1996) are still unanswered.

Humidity measurements are predominantly obtained by either humidity gauges, radiometers, radiosondes or satellite systems, as reviewed by Bevis et al (1992):

**Humidity gauges** frequently deployed at meteorological surface stations, often rely on measuring some other parameter, such as weight, pressure, temperature or mechanical or electrical variations in a material as it absorbs humidity. Through calibration and calculation, these measured values can provide a measurement of moisture. Modern electronic devices are typically based on the principle of measuring condensation temperature, or differences in resistance/electrical-capacitance to measure moisture. However, these instruments commonly provide only very local, point, observations, and therefore suffer from low spatial resolution. On the other hand, moisture is a field that may be highly variable in the mesoscale (e.g. Lilly and Gal-Chen, 1983; Fabry, 2006). Consequently, these measurements are often not representative for the spatial scale required e.g. for model grid boxes (Fabry, 2006). Compounding this problem is the limited accessibility to position humidity gauges in heterogeneous terrain, or areas with complex topography. Moreover, possible surface perturbations may interfere with the ability to conduct accurate measurements (WMO, 2008) since these instruments typically installed, for example, 2m from the ground as in e.g. standard meteorological surface stations.

**Radiosondes** are instruments, carried (by a balloon) or dropped (from an aircraft or rocket- known as dropsondes) through the atmosphere, that are equipped with devices to measure humidity (and in some cases additional meteorological variables, such as pressure, temperature, etc.) These instruments transmit measurements over radio to an observing station (WMO, 2008). Radiosondes provide important, in situ measurements, with reasonable vertical resolution on the synoptic scale, but there are serious disadvantages as well. The cost of these expendable devices restricts the number of launches to 2-4 daily at a limited number of sites. These restrictions mean that radiosondes provide inadequate measurement resolution for the spatial and temporal variability of humidity (Fabry, 2006).
**Water Vapor radiometers** (WRVs) are ground-based, upward-looking instruments that measure the background microwave radiation produced by atmospheric water vapor. WVRs can estimate the integrated water vapor (IWV) content, as well as the integrated liquid water (ILW) along a given line of sight, simultaneously. WVRs actually measure sky brightness temperature at two or more frequencies. The frequency dependence of the brightness temperature enables the WVR to simultaneously estimate the IWV and ILW (Resch, 1984). The algorithm for calculating IWV from sky brightness temperature observations includes parameters which show seasonal and site variations. Thus, this algorithm usually needs to be “tuned” for local conditions using independent meteorological data (usually from radiosondes).

**Space Based radiometers** are downward-looking WVRs. Upward-looking WVRs measure water vapor emission lines against the cold background of space. Downward-looking WVRs measure the corresponding absorption lines in the radiation from the hot background of the Earth. IWV recovery by space-based WVRs is complicated over land because the background temperature is highly variable, and difficult to determine. This is further complicated in the presence of cloud, because the background temperature may be different on Earth's surface and on cloud top. While it is possible in principle to model these effects, it is, in most cases a difficult and time consuming task. For this reason satellite-based WVRs tend to be more useful over ocean, and their utility is degraded in the presence of clouds. On the other hand, surface level moisture is, in most cases, a most important variable for convection. Ground-based WVRs are not affected by light or moderate clouds, but their performance may be degraded under heavy cloud cover, and precipitation negates the usefulness of most, if not all, of these instruments. Thus, ground and space-based WVRs are complementary – Ground based units provide good temporal but poor spatial coverage, while space-based WVRs provide the opposite.

**The global positioning system** (GPS) is a constellation of satellites transmitting L band (1.2 and 1.6 GHz) radio signals to large numbers of GPS receiver users who utilize the system for navigation, time transfer, and relative positioning. Since water vapor slows the propagation speed of the GPS microwaves, it is possible to determine the “zenith wet delay” caused by the troposphere over each GPS receiver in the network. This delay is nearly proportional to the amount of precipitable water over the
GPS site (Hogg et al., 1981; Resch, 1984), and thus GPS networks are employed for remote sensing of the atmosphere (Bevis et al., 1992).

GPS precipitable water vapor estimates have been shown to have high accuracy when compared with radiosonde and WVR data. Additionally, GPS provides high temporal resolution (e.g. 5 minutes), all-weather capability, and is relatively low cost. Spatial coverage is a key disadvantage, though. Very limited GPS measurements can be collected in polar regions or over the oceans, if any, and even in dense GPS networks, such as the Southern California Integrated GPS Network (SCIGN), or the world's largest nationwide network, Japan's GEONET, station spacing ranges from a few kilometers, to tens of kilometers, which is not sufficiently dense for many applications (Li, 2004).

1.1.3 Sudden Rainfall monitoring in dry climate regions

Dry climate, which can be further classified into arid and semi arid climate types, cover more than a quarter of the world's land area (Ahrens, 2003; Morin et al., 2009). However, precipitation data from these climatic environments, typified by severe water-scarcity, are severely lacking in comparison to more inhabited regions. Real time rainfall monitoring in such areas is of high importance from several different points of view. Although the total precipitation amounts in dry regions are low, the percentage of intensive rainfall events, generated by severe convection, is major. At the same time, in addition to precipitation, shallow soil with sparse vegetation, a quick decay of the infiltration curve, areas of bare rock, and large inclines of the ravines lead to high levels of peak flow and to the eruption of flash floods (e.g. Cohen et al., 2010; Greenbaum et al., 2006).

Moreover, as a result of the combination of these conditions, the soil erosion due to water is particularly high comparing to other climatic zones. Accelerated erosion by water (and wind) in dry regions is one of the causes of desertification and it exacerbates soil degradation (e.g. Lal, 2001). In addition, especially in warm semi arid and desert fringe regions, precipitation plays a significant role as a factor triggering epidemics (Grover-Kopec et al., 2005). Finally, it has been shown that rainfall patterns have a strong impact on vegetation related processes as well as on the entire (arid and semi arid) ecosystems (e.g. Lazaro et al., 2001; Rietkerk et al., 2002).
On the other hand, desert areas, such as those presented in this research, are particularly problematic for monitoring as the current measuring methods, if existing at all, provide only very limited precipitation data. State of the art rainfall observation systems include surface stations (rain gauges), weather radiosondes and remote sensing systems - radars and satellites. However, these techniques are expensive, not widespread and are often insufficient in their accuracy or in temporal/spatial resolution, especially close to the ground.

Conventional rain gauges, found at surface stations, provide an accurate measurement, but they measure locally, at a single point. In addition, the sparse deployment in dry areas cannot precisely represent precipitation change spatially in stormy rain events (e.g. Michaud and Sorooshian, 1994). Even if the number of gauges in a specific region was much higher, the ability to detect precipitation in a wide area based on this form of measurement would still be small. The probability that a single convective cell will miss the rain gauge entirely is high. Furthermore, even if precipitation were registered in one of the gauges, the likelihood of that particular gauge representing the maximum rainfall in the region is low.

Remote sensing systems provide a large amount of data over large spatial and temporal spans, and have greatly improved the ability to monitor precipitation in these areas. Of these remote sensing systems, the most common for precipitation measurements is the weather radar (Raghavan, 2003). These systems typically provide precipitation data every 5 minutes with a spatial resolution of 1 km². The range covered by a typical radar system normally stands at around 30,000 km² (Morin et al., 2009).

Advanced weather radars can provide a wide range of detailed information about precipitation and the dynamics of rainstorms, from rainfall intensity and wind velocity, to the type and vertical structure of precipitation (Verlinde et al., 2002). Moreover, weather radars have shown to be useful in extending the predictability of flash floods in semi arid regions (e.g. Morin et. al, 2009). Despite this, radar data have had limited quantitative use in meteorological applications, because of errors and uncertainty in the surface precipitation estimates derived from it (Harrison et al., 2000). These errors and uncertainties are the outcomes of several factors, such as: calibration issues, the spatial expansion effect of the radar beam and problems with partial beam filling, problems with beam overshooting (Durden et al., 1998; Gabella
et al., 2013) and high sensitivity of the rain rate-reflectivity relation to DSD variations (Jameson, 1991). In addition, dry desert areas are quite often not covered by radars.

Satellite instruments provide the ability to measure rainfall over remote regions of land and water where data are difficult or impossible to collect. As reviewed by Jobard (2001): starting in the 1970s, Visible light (Vis) and Infrared (IR) imagers on board geostationary satellites were used (e.g. Meteosat-1 launched in 1977). In the late 1980s passive microwave radiometers were put in use, such as the Special Sensor Microwave / Imagers (SSM/I) carried on board the series of DMSP polar orbiting satellites, starting in 1987. Then, in 1997, the first mission specially dedicated to precipitation measurement, the Tropical Rainfall Measuring Mission (TRMM) was launched on a tropical orbit, carrying Vis, IR and MW radiometers and the first space borne precipitation radar.

However, a key problem for all of these methods is the very indirect relation between precipitation on the ground and that measured by the satellite signal (e.g. Seyyedi, 2010). Measurements in the microwave spectral range rely on the absorption of the microwave radiation by liquid water, or the scattering by ice particles. The amount of precipitation reaching the ground, however, also depends on the structure of the atmospheric layer under the precipitation cloud. Infrared satellite data is an even more indirect approach. Cloud top temperature is only for convective systems directly related to the surface rainfall, and even in these cases the amount of precipitation depends strongly on the stage in the life cycle of the convective system.

To sum up, it is obvious then, that the ideal measurement method would provide fog, moisture and rainfall data from a wide spatial range, as the radar and satellites do, with close proximity to the ground, as is the case with meteorological station gauges, directly from the areas of interest, at low costs. The advantage of hydrometeors measurement using existing microwave networks is that it combines these exact characteristics (Upton et al., 2005; Messer et al., 2006). Cellular network infrastructure already covers large land areas all over the world, including regions that are difficult to access, such as complex topography, and particularly arid and semi arid zones where other techniques are often insufficient. Furthermore, what is ideally required for meteorological modeling purposes is an area average measurement of

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near-surface observations over a box with the scale of the model’s grid and at an altitude of a few tens of meters. Current measuring tools often cannot provide this type of data effectively (e.g. Ducrocq et al., 2002; Fabry, 2006; Gultepe et al., 2007). The technique presented here has the potential to provide this exact type and resolution of measurement.

1.2 MICROWAVE ATTENUATION DUE TO ATMOSPHERIC PHENOMENA

In the microwave region (0.3 GHz- 300 GHz, Sorrentino and Bianchi, 2010) losses are generally negligible in the atmosphere in frequencies of up to 5 GHz. However, above 10 GHz, losses due to atmospheric phenomena become important. The total transmission loss for millimeter wave links can be described as follows (Freeman, 1991; Frey, 1999):

\[
\text{Transmission loss} = 92.45 + 20\log_{10}(f) + 20\log_{10}(L) + \psi
\]  

(1)

Where \(f\) (GHz) is the radio frequency and \(L\) is the ML length (km). For detailed derivation of this equation see (Zinevich, 2010). Let us focus on the total atmosphere induced attenuation component- \(\psi\) (dB). This parameter includes attenuation as a result of atmospheric phenomena, in particular: rainfall and sleet, water vapor, fog, oxygen and other gases/pollutants. Several atmospheric gases and pollutants have absorption lines in the microwave region, e.g. \(\text{SO}_2\), \(\text{NO}_2\), \(\text{N}_2\text{O}\). However, their effect is negligible due to their low density (e.g. Meeks, 1976; Frey, 1999; Raghavan, 2003). The information concerning the attenuation and absorption by oxygen (and water vapor) is based on the pioneering work of Van Vleck (Van Vleck, 1947a, 1947b). Oxygen molecules have an absorption band around 60 GHz and a single resonance line at 118.75 GHz.

In the frequency range between 6 and 40 GHz, though, which is typical to commercial microwave systems, and on which we focus in this work, the variations caused to the signal as a result of interaction with Oxygen molecules are negligible with respect to the attenuation caused by the atmospheric hydrometeors (below, see also section 3.2.2). The work concentrates, then, on three primary parameters affecting microwave networks in this frequency range: Precipitation, atmospheric water vapor and fog.
In the following sections we shall develop the physical expressions and describe the microwave attenuation models caused by each of these three fundamental meteorological parameters of interest.

1.2.1 Fog induced attenuation

The total cross section \( Q(a, \lambda) \) is a quantity with the dimensions of an area and is a function of the radius \( a \) of a fog droplet, and the radiation wavelength \( \lambda \). It represents the depletion of energy by absorption and dissipation as heat on the one hand and by scattering, on the other hand (Raghavan, 2003):

\[
Q(a, \lambda) = Q_s + Q_a
\]  

\( Q_s \) is the scattering cross section and \( Q_a \) the absorption cross section. According to the Mie theory (Kerr, 1951; Raghavan, 2003):

\[
Q(a, \lambda) = \frac{\lambda^2}{2\pi} \sum_{m=1}^{\infty} (2m+1) \text{Re}\{a_m + b_m\}  
\]  

The coefficients \( a_m = a_m(x, \tilde{n}) \) and \( b_m = b_m(x, \tilde{n}) \) represent the amplitudes of the field distribution due to the magnetic and electric multipoles, respectively, which are induced by the incident wave (\( m=1 \) represents the dipole; \( m=2 \) corresponds to the quadrupole and so on). \( a_m \) and \( b_m \) are functions of the Mie size parameter \( x \equiv \frac{2\pi a}{\lambda} \) and the complex refractive index \( \tilde{n} \).

For fog consisting of entirely small droplets, generally of the order of up to several tens of microns (e.g. Herckes et al, 2007), the Rayleigh approximation \( (x<1) \) is valid for frequencies below 200 GHz. In this case the higher orders of \( a_m \) and \( b_m \) in equation (3) are neglected, and we get:

\[
Q_s = \frac{\lambda^2}{2\pi} \cdot \frac{4}{3} x^4 \left| \frac{\tilde{n}^2 - 1}{\tilde{n}^2 + 2} \right|^2  
\]  

\[
Q_a = \frac{\lambda^2}{2\pi} \cdot 2x^3 \text{Im}\left(\frac{\tilde{n}^2 - 1}{\tilde{n}^2 + 2}\right)  
\]
Under these conditions, $Q_a$ which is proportional to $x^3$ is far larger than $Q_s$ which is proportional to $x^6$. Hence the latter can be neglected and the total cross section $Q$ is approximately equal to $Q_a$.

The reduction $dP$ in the incident power $P$ transmitted over a path length $dr$ is given by:

$$dP = -\left(\sum Q\right)Pdr$$

(6)

Where $\sum Q$ is the sum of the attenuation cross sections of the particles in unit cross section and unit length (i.e. in unit volume).

If we consider the attenuation due to all fog droplets in the path length $L$ of unit cross section, the reduction of power over the distance is given by integrating over a range $0$ to $L$:

$$\ln \frac{P_L}{P_0} = -\int_0^L (\sum Q)dr$$

(7)

Hence,

$$10 \log \frac{P_L}{P_0} = -\frac{\lambda^2}{2\pi} 2\sum x^3 \text{Im}\left(\frac{\tilde{n}^2-1}{\tilde{n}^2+2}\right) = 0.4343 \frac{8\pi^2}{\lambda} \sum a^3 \text{Im}\left(\frac{\tilde{n}^2-1}{\tilde{n}^2+2}\right)$$

(8)

Equation (8) gives the attenuation in dB·km$^{-1}$, also called specific attenuation, if we put $L=1$ km and take the summation of $Q$ in cm$^2$ over a volume of 1 m$^3$, $\lambda$ being in cm.

The fog liquid water content (LWC) in unit volume (g·m$^{-3}$) is:

$$LWC = \frac{4}{3} \pi \rho_w \sum a^3$$

(9)

$\rho_w$ being the density of water (g·cm$^{-3}$). Hence, the attenuation $A_f$ in dB·km$^{-1}$ is:

$$A_f = 10 \log \frac{P_L}{P_0} = 0.4343 \cdot 6\pi \cdot LWC \lambda^{-3} \rho_w^{-1} \text{Im}\left(\frac{\tilde{n}^2-1}{\tilde{n}^2+2}\right)$$

(10)

While the density of water is $\rho_w=1$ g·cm$^{-3}$, and $f$ is in GHz, the following expression is obtained:

$$A_f = 0.273 \cdot LWC \cdot f \cdot \text{Im}\left(\frac{\tilde{n}^2-1}{\tilde{n}^2+2}\right) \equiv \Phi \cdot LWC$$

(11)

Figure 2 presents the theoretical expected attenuation per 1 km created by fog (based on Rec. ITU-R P.840-4, 2009), as a function of typical commercial MLs frequencies. The LWC within fogs typically ranges between 0.01 to 0.4 gr/m$^3$ (Gultepe et al.,
The calculations presented in Fig. 2 were made for different LWC values starting at 0.1 gr/m$^3$, and at different temperatures (10 and 15 °C). The maximum values of LWC were taken from field measurements (including five minute average values) carried out in the conducting of recent comprehensive field campaigns in different places in the world, using specialized equipment (Klemm et al., 2005; Herckes et al., 2007; Gultepe et al., 2009; Niu et al., 2010). The expected signal loss was calculated using Eq. (11). The horizontal dashed line indicates the typical measurement resolution of commercial MLs (links with a coarser measurement resolution exist, but will not be the focus of the current section). Notably, that for longer links (Fig. 2b), the effective sensitivity per km increases, and lighter fogs can potentially be detected.

![Fig. 2. Transmission loss due to fog. Signal attenuation per 1 km (a) and 5 km (b) created by different levels of fog concentration at temperatures of 15 (red) and 10 (blue) °C, as a function of the ML operating frequency. The dashed line (black) indicates a typical measurements resolution of commercial MLs (0.1 dB). Given a certain LWC value, the expected attenuation is greater for higher frequencies, at lower temperatures (ITU-R P.840-4, 2009).](image-url)
1.2.2 Water vapor induced attenuation

At frequencies of tens of GHz, the main absorbing gases in the lower atmosphere are oxygen and water vapor. While oxygen has an absorption band around 60 GHz, water vapor has a resonance line at 22.235 GHz (Van Vleck, 1947a; Van Vleck, 1947b). Although other atmospheric molecules have spectral lines in this frequency region, their expected strength is too small to affect propagation significantly (Meeks, 1976; Frey, 1999; Raghavan, 2003). As a consequence, an incident microwave signal, interacting with the H$_2$O molecule is attenuated, particularly if its frequency is close to the molecule's resonant one.

The refractive index

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

$$v = (\varepsilon' \mu')^{-1/2}$$ (12)

Where:

$\varepsilon'$ (A$^2$·s$^4$·Kg$^{-1}$·m$^{-3}$) - The permittivity of the medium.

$\mu'$ (m·Kg·s$^{-2}$·A$^{-2}$) - The magnetic inductive capacity of the medium.

In free space, the velocity of light, $c$, is known as follows:

$$c = (\varepsilon_0 \mu_0)^{-1/2}$$ (13)

While:

$\varepsilon_0 = 8.85 \times 10^{-12}$ (A$^2$·s$^4$·Kg$^{-1}$·m$^{-3}$) - The permittivity of free space.

$\mu_0 = 4\pi \times 10^{-7}$ (m·Kg·s$^{-2}$·A$^{-2}$) - The magnetic inductive capacity of free space.

The dielectric constant of the medium, $\varepsilon_r$, which expresses the extent to which a material concentrates electric flux, is defined as the following ratio: $\varepsilon'/\varepsilon_0 = \varepsilon_r$. The ratio $\mu'/\mu_0 = \mu$ signifies 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:
\[ n = \frac{c}{\nu} = (\varepsilon \mu)^{1/2} \]  

(14)

Thus, for the propagation medium considered here, the value of \( \mu \) can be taken as unity and therefore:

\[ n^2 = \varepsilon \]  

(15)

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

**The absorption coefficient - \( \Gamma \)**

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

\[ \tilde{E}(z,t) = E_0 e^{i(\tilde{k}z - \omega t)} \tilde{\eta} \]  

(16)

\[ \tilde{B}(z,t) = B_0 e^{i(\tilde{k}z - \omega t)} (\hat{z} \times \tilde{\eta}) \]  

(17)

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

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

\( \tilde{k} \) - The complex wave-number (rad/m).

\( \omega \) - 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 \( \tilde{s} \). The average in time, \( s_a \), of the magnitude of the Poynting vector is expressed as (Kerr, 1951; Raghavan, 2003):

\[ s_a = \frac{1}{2} \text{Re}(\tilde{E} \times \tilde{H}^*) \]  

(18)

The asterisk signifies the complex conjugate while the vector \( \tilde{H} \), associated with the magnetic field \( \tilde{B} \), is given in equation (19):
\[ \mathbf{B} = \mu \mathbf{H} \]  

(19)

The intensity, \( I \), of an electromagnetic wave is proportional to \( s_a \) (Jackson, 1999). Therefore, by substituting equations (16), (17) and (19) into equation (18):

\[ I(z) \propto e^{i(\mathbf{kz} - \omega t)} = e^{-2\text{Im}(\mathbf{k})z} \]  

(20)

Hence:

\[ I(z) = I_0 e^{-2\text{Im}(\mathbf{k})z} \]  

(21)

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:

\[ I(z) = I_0 e^{-\Gamma z} \]  

(22)

While \( \Gamma \) (m\(^{-1}\)) is the absorption coefficient.

Hence:

\[ \Gamma = 2\text{Im}(\mathbf{k}) \]  

(23)

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

\[ \tilde{n} = \text{Re}(\tilde{n}) + i\text{Im}(\tilde{n}) = \frac{c\mathbf{k}}{\omega} = \frac{c\text{Re}(\mathbf{k})}{\omega} + i\frac{c\text{Im}(\mathbf{k})}{\omega} \]  

(24)

Therefore, from equations (23) and (24):

\[ \Gamma = \frac{2\omega}{c} \text{Im}(\tilde{n}) = \frac{4\pi f}{c} \text{Im}(\tilde{n}) \]  

(25)

Finally, in order to obtain \( \Gamma \) in dB/km:

\[ \Gamma(dB/\text{km}) = \left[ \frac{10}{\ln 10} \right] \frac{4\pi f[GHz] \cdot 10^9}{[N[GHz]] \cdot 10^{-6}} \left[ \frac{N[N \text{units}]}{3 \cdot 10^5 [\text{km/s}]} \right] \]  

(26)

\[ = 0.1820f[GHz]^{N[N \text{units}]} \]
While $N''$ is the imaginary part of the refractive index in N units (the index of refraction, $n$, is equivalent to $(n-1) \cdot 10^6$ N units).

Figure 3 presents the theoretical expected attenuation per 1 km (Fig. 3a) and 5 km (Fig. 3b) created by different water vapor concentrations at 15 °C as a function of typical commercial MLs frequencies. The calculation was made for a humidity range between 25% and 100% matching a water vapor concentration of between 3 and 13 gr/m$^3$, respectively, at sea level pressure (Rec. ITU-R P.676-6, 2005; David et al., 2009). A noticeable absorption line can be seen around the 22.2 GHz range (Van Vleck, 1947a). Notably, the effective magnitude resolution per km increases with link length (while on the other hand the spatial resolution decreases since the measurements are averaged a longer path).

![Fig. 3. Transmission loss due to water vapor as a function of microwave frequency. The percentages indicate relative humidity. The horizontal line indicates the typical magnitude resolution of a commercial microwave link, and specifically that of the system used for this part of the research (0.1dB). The attenuation values shown are calculated from approximations to the model (Rec. ITU-R P.676-6, 2005)
1.2.3 Rainfall induced attenuation

The interpretation and modeling of atmosphere-induced impairments on radio links have been researched by telecommunication specialists for years (e.g. Olsen et al., 1978; Rec. ITU-R P.838-2, 2004).

The absorption and scattering of electromagnetic waves by raindrops, distributed at a point $s$ along an $L$ km link as drop size distribution $N_d(D, s)$, causes path-integrated rainfall-induced attenuation ($A_p$). $D$ signifies the equivalent rainfall drop diameter and $Q_d$ is the extinction cross-section at a given frequency and polarization (Atlas and Ulbrich, 1977; Zinevich et al., 2010):

$$A_p = 0.4343 \int_0^L ds \left( \int_0^D dDN_d(D, s)Q_d(D) \right) = 0.4343 \int_0^D dD\bar{N}_d(D, L)Q_d(D)$$  \hspace{1cm} (27)

Where $\bar{N}_d(D, L) = \int_0^L dxN_d(D, x)$ is the path-integrated DSD. Similarly, the path-averaged rainfall $R_L$ is given by:

$$R_L = \frac{0.6\pi}{L} \int_0^D dD\bar{N}_d(D, L)V_d(D)D^3$$  \hspace{1cm} (28)

$V_d(D)$ denotes the terminal velocity of the raindrop. Both $V_d(D)$ and the scattering cross-section can be approximated by power laws $V_d(D) = 3.78D^{0.67}$, $Q_d(D) = CD^9$ (Atlas and Ulbrich 1977), and thus $A_p$ and $R_L$ can be considered higher-order moments of $N_d(D)$.$^5$ Relatively large raindrops- characterized by diameters exceeding 1 mm, are of flattened shape (Oguchi, 1983). Consequently, the extinction cross-section of these drops for a horizontally-polarized wave is larger than that for vertically-polarized one. Accordingly, these physical characteristics lead to lower rainfall-induced attenuation for the latter under the same conditions (Rec. ITU-R P. 838-2, 2004).

The stochastic relationship between $A_p$ and $R_L$, for a given link, can be obtained empirically by fitting their estimates based on the DSD measurements of $N_d(D,L)$ for a given link length $L$.

$^5$ At frequencies of about 34 GHz, where the power $n$ in the cross-section expression equals that of $V_d(D)$ the relation between $A_p$ and $R_L$ becomes linear.
Several models, relating $A_P$ (given in dB/km) with $R_L$ (mm/hr), exist. One accepted approach is the power law model for the attenuation described as (Olsen et al., 1978):

$$A_P = aR_L^b$$  \hspace{1cm} (29)

Where the constants $a$ and $b$ are functions of frequency, polarization and DSD (Jameson, 1991). The expected rainfall induced attenuation due to different rain intensities is illustrated in Fig. 1.

### 1.3 Motivation - Commercial MLs as an Opportunistic System for Monitoring Atmospheric Hydrometeors

In Europe and Asia, MLs have grown to become the predominant form of cellular backhaul technology, and account for the majority of cellular base station connections (Messer et al., 2006; Zinevich, 2010).

The incredible spread of existing commercial microwave systems provides, for the first time, an opportunity to receive measurements from locations where, up to this point, data did not exist, due to limited deployment of existing monitoring equipment, or limitations of remote sensing systems (Satellites, radar) in geographical regions with complex terrain, steep slopes, desert regions, and more (e.g. David et al., 2013b).

Figure 4, which exemplifies the widespread areal deployment of microwave links, shows the link systems operated by three cellular providers in Israel.

In particular, there is a basic shortage of conventional monitoring instruments in developing and third world countries (e.g. Mul, 2009) where, on the other hand, microwave based cellular communication networks are already deployed (e.g. Doumounia et al., 2013). This being the case, the newly available data are of extraordinary value.

The general problem of representativeness is particularly acute in the measurement of atmospheric parameters using conventional ground level monitoring techniques. The point observations obtained are particularly sensitive to exposure e.g. of surface perturbations, wind and topography (WMO, 2008). Observations derived from microwave networks have the advantage of being taken relatively close to ground
level (several tens of meters) just like in the case of surface installed proprietary measurement instruments (e.g. humidity, visibility, and rain gauges) while at the same time covering a wide geographical area, allowing for large spatial resolution such as that provided by satellite and radar systems. The combination of these two characteristics allows for the creation of a unique environmental observation system that can improve upon the representativeness problems of existing tools.

Fig. 4: Commercial MLs distribution across Israel. MLs whose received signal measurements were available for this research. Total number of links: ~10,000. Different networks are depicted in different colors: purple – Cellcom™ PDH\(^6\) links (once per day measurements, magnitude resolution: 0.1 dB), green – Cellcom™ (temporal resolution: 15 min, magnitude resolution: 1 dB), pale blue – Cellcom™ SDH\(^7\) (15 min, 0.1 dB) and dark blue is Pelephone™ network (1 min, 1 dB), orange – Orange™ SDH (once per day measurements, 0.1 dB).

\(^6\) Plesiochronous Digital Hierarchy
\(^7\) Synchronous Digital Hierarchy
The approach in this research is that the microwave system is a given existing installation, presenting the challenge of using the system, without changing any of the selected or structural parameters, while contending with the built in limitations: predefined time (e.g. once per 15 minutes, once per day) and magnitude resolution of the sample (e.g. 0.1 dB, 1 dB), set operating frequencies, the specific geographic deployment of the links, part of the MLs systems are equipped with Automatic Transmit Power Control (ATPC), which means that in such cases records of the transmitted signal level should be taken into account in addition to the RSL in order to analyze the signals. In some cases the system logs only maximum and minimum RSL measurements over time intervals of 15 minutes. While the quality of the observation determined from a single link is non-optimal, the vast amount of data available from multiple links of various lengths and frequencies allow for a considerable improvement in the quality of observation.

Figure 5 presents the different link lengths and operating frequencies (based on the system of a single cellular provider).

Fig. 5: Commercial MLs lengths vs. frequencies (Source: Messer and Sendik, 2013). The figure is based on links data from one cellular provider (Cellcom). The figure presents 7030 links operating in the range between approximately 17 and 39 GHz deployed over lengths from several tens of meters up to approximately 30 kilometers. The system is designed so that at least two links, operating in adjacent frequencies separated by around 1 GHz, are deployed over each physical path (a total of 3515 pairs). Each link pair is indicated by a black and a grey dot. Black dots – indicating an operating frequency transmitted from one end of the link to the other (at the higher operating frequency), and in gray – the transmission frequency from point 2 to point 1 (at the lower operating frequency).
An added advantage of this no-involvement with the standard system parameters approach is the global applicability of the methods, i.e. the ability to apply these techniques in different regions and different networks with minimum effort (Zinevich, 2010).

1.4 RESEARCH OUTLINE AND GOALS

The goal of the current work is to prove the feasibility, and the potential that exists in already existing commercial microwave systems to monitor atmospheric water vapor, detect fog and asses its intensity. The feasibility of monitoring rainfall has been shown previously (Messer et al., 2006; Leijnse et al., 2007). In the third part of the research, the relative advantage and the potential of using this method is shown in regions prone to floods and remote areas where rain gauges and radar systems do not, at times, provide sufficient information.

Chapter II presents the research methodology. This chapter details the methods for monitoring the different phenomena through the use of physical and empirical models. These models are utilized for estimating the concentration and intensity of each observed hydrometeor, given the weather related induced attenuation derived from commercial MLs. Preprocessing of the raw data and expanded detail regarding the different techniques used or developed specifically for this research are described.

Chapter III presents the results of the research. All of the results presented here are based on standard real data which were received from commercial cellular providers in Israel (Cellcom™, Pelephone™, Orange™). The microwave data were measured during several rainfall, humidity and fog events that took place at different times and in different regions of the country. The results are compared to measurements of specialized monitoring instruments received from official meteorological organizations in Israel.

Chapter IV presents the research conclusions. The discussion focuses on, among other issues, the advantages and disadvantages of the proposed methods, the limitations of the techniques, the potential of the novel approach, and suggestions for future research.
CHAPTER II

METHODOLOGY

The effects of the different atmospheric phenomena on the microwave system differ according to each phenomenon's particular characteristics. Effects can create differing levels of signal attenuation depending on frequency, and signal polarization. Different meteorological phenomena may differ in their spatial scale, their duration, and in some cases their typical timing during the day or season. Combining this and/or additional information with the direct measurements of the microwave systems can allow for distinguishing between the different phenomena. To concentrate on the proof of feasibility, the discussion in this work was limited to the potential of monitoring a single phenomenon, during each case. The use of additional meteorological side information assists in ruling out, or minimizing the effects of other phenomena that may occur simultaneously with the phenomenon attempted to be measured.

2.1 FOG IDENTIFICATION AND ESTIMATION USING MEASUREMENTS FROM MULTIPLE MLs

Two fundamental stages in fog monitoring using measurements from multiple MLs are distinguished here: identification of the fog phenomenon, and the estimation of its degree using additional standard meteorological instruments (temperature, humidity and rain gauges).

As the primary aim is to prove the feasibility of the proposed methodology, the technique was restricted to situations where other hydrometeors (rainfall, sleet, snow) were nonexistent along the propagation path and the research was centered on extreme fog events.
2.1.1 Fog Identification

We take a set – \( L_1, \ldots, L_N \) - of MLs spread across the observed region within the same fog patch. In a typical cellular backhaul network (e.g. Zinevich et al., 2008), microwave links at different lengths and direction exist at an area of a size similar to a dense fog field, e.g. of the order of several \( \text{km}^2 \) (e.g. Pagowski et al., 2004). The availability of diverse RSL measurements enables to identify the fog induced component with higher statistical precision.

A simplified model describing the attenuation of the \( i \)-th total atmosphere induced attenuation, \( \psi_i \), can be described as follows (Zinevich et al., 2010):

\[
\psi_i = [A_{fi} + A_{pi} + A_{wi} + A_{vi} + Noise_i]_{qi} \quad \text{(dB)} \quad (30)
\]

Where the index \( i \) signifies the attenuation as measured by the \( i \)-th ML, let us denote:

- \( A_{fi} \) - Fog induced attenuation.
- \( A_{pi} \) - Attenuation as a result of other-than-fog precipitation (rain, sleet, snow).
- \( A_{wi} \) - Wet antenna attenuation. Because of the high level of humidity during fog, a thin layer of water may accumulate on the outside covers of the microwave antenna and may create additional attenuation to the received signal, beyond that caused by the fog in the atmospheric path.
- \( A_{vi} \) - Water vapor attenuation
- Noise\(_i\) - All other random signal perturbations, e.g., which created as a result of winds that may oscillate the antennas, variations of the atmospheric refractive index, or temperature variations which may affect the analogue circuitry of the microwave units (Leijnse et al., 2007a; Zinevich et al., 2010).

[ ]\(_qi\) - Each of the attenuation measurements, \( \psi_i \), is quantized according to the given magnitude resolution of each commercial ML.

In this study it is assumed that \( A_{pi}=0 \). This assumption is validated using nearby standard measurements of rain gauges and temperature meters.

In order to estimate the amount of wet antenna attenuation, \( A_{wi} \), and if it did in fact occur, let us make use of measurements over particularly short MLs (preferably of up to a few hundreds of meters long) that are located near longer links, since the effect of
fog, even a heavy one, as well as of water vapor on the signal attenuation at such short ranges is much smaller comparing to the attenuation created in longer MLs of several km in lengths (Rec. ITU-R P.676-6, 2005; Rec. ITU-R P.840-4., 2009). This being the case, any additional attenuation, if detected, can be directly attributed to the layer of water on the antennas, its value measured, and that value can be used to adjust the measurements on the longer links.

In order to identify the specific attenuation created as a result of the fog itself, a baseline, zero RSL value was set separately for each link. Since the density of water vapor in the atmosphere affects MLs (Rec. ITU-R P.676-6, 2005; David et al., 2009, 2011) and since humidity is particularly high during fog, the zero level can be chosen by selecting the median value from RSL measurements taken over a period of several hours, during which the relative humidity in the area, as measured by the meteorological stations at the site, is around 90%. Alternatively, since the humidity difference between the foggy day and the reference day is known, the median RSL from the days adjacent to the event can be chosen (e.g. in cases where measurement occurs once daily), and a humidity correction to the baseline is carried out using a known physical model (Rec. ITU-R P.676-6, 2005). By this selection of the base line, the water vapor effect, $A_v$, is minimized and is assumed to be zero.

Thus, fog is identified as being present when the measured RSL value crosses the predefined threshold during times of high relative humidity (of ~95% and more), while the additional attenuation is observed simultaneously by the numerous MLs spread across the area.

### 2.1.2 Fog Density Estimation

After detection of the existence of fog, the average amount of LWC per unit of volume in the fog was calculated, from which a rough estimation of the range of visibility was acquired.

#### 2.1.2 A Liquid water content calculation

At the end of stage 2.1.1 we are left with the following, while $\gamma_i$ signifies the attenuation as measured by the $i$-th ML:
\[
\gamma_i = A_{fi} + A_{wi} + \tilde{\text{Noise}}_i \quad \text{(dB)} \quad (31)
\]

The effective noise component as defined here, $\tilde{\text{Noise}}_i$, includes the contribution from system quantization error.

The relation between the fog induced attenuation, $A_{fi}$, and the total water content per unit volume is given by (Rec. ITU-R P.840-4, 2009):

\[
A_{fi} = \Phi_i \cdot LWC \cdot L_i \quad \text{(dB)} \quad (32)
\]

Where $L_i$ (km) is link length, $\Phi_i$ is a frequency and temperature dependent coefficient (known parameters), and $LWC$ is the liquid water content (g m$^{-3}$). In this work, it is assumed that all links deployed across the same fog field observe at the same time the same LWC.

Given $\gamma_i$ measurements from N links operating around the same frequency and over the same fog patch, the effective fog induced attenuation, $\hat{a}_f$, can be extracted from N equations as (31) by a least squares or other estimation method, and provide better accuracy than in the case of measurement from a single link:

\[
\gamma_i = \hat{a}_f \cdot L_i + \hat{A}_w + \tilde{\text{Noise}}_i \quad \text{(dB)} \quad (33)
\]

While:

\[
\hat{a}_f = \Phi \cdot LWC \quad \text{(dB/km)} \quad (34)
\]

Consequently, the LWC within the fog field is derived through the known relation (34).

$\hat{A}_w$ is the estimated wet antenna component.

A mathematical model (ITU-R P.840-4, 2009) based on Rayleigh approximation is used for the calculation of $\Phi$, for frequencies of up to 200 GHz (fog drops typically range in size from several microns to a few tens of microns (e.g. Herckes et al., 2007; Gultepe et al., 2009), i.e. small with respect to millimeter microwaves):

\[
\Phi = 0.819 f \cdot [\varepsilon''(1 + \beta^2)]^{-1} \quad \text{(dB/km)/(g/m}^3) \quad (35)
\]

With $f$ being the link frequency (GHz), while:
\[
\beta = (2 + \varepsilon')/\varepsilon''
\]  

(36)

The complete expression of the complex dielectric permittivity of water
\[\varepsilon(f) = \varepsilon'(f, T) + i\varepsilon''(f, T),\]
is detailed in literature (Rec. ITU-R P.840-4, 2009).

2.1.2 B Visibility estimation

In order to estimate the visibility (WMO, 2008) - \(V\) the following warm-fog visibility parameterization was used (Gultepe et al., 2006). This formula takes into account the droplet number concentration, \(N_D\), in addition to the LWC:

\[V = 1.002 \cdot (LWC \times N_D)^{-0.6473} \quad \text{(km)} \quad (37)\]

The formula is suitable for warm fog (\(T > 0^\circ C\)) conditions. \(N_D\) can be measured directly using specialized equipment. This value can be roughly estimated given the temperature, \(T\), by using the following known relation (Gultepe and Isaac, 2004):

\[N_D = -0.07 T^2 + 2.213 T + 141.56 \quad \text{(cm}^3) \quad (38)\]

A rough range of \(V\) is acquired based on maximum and minimum bounds derived from the uncertainty in estimating this parameter.

2.1.3 Uncertainty and bounds on the visibility estimate

2.1.3A Liquid water content

The dominant source of uncertainty in estimating the LWC is the uncertainty in estimating the effective fog induced attenuation, \(\hat{a}_f\). In order to estimate the error in this value let us use the error estimation formula for a linear slope (Kenney and Keeping, 1962):

\[\Delta \hat{a}_f = \sqrt{\sum (y_i - \hat{y}_i)^2 \cdot \left[(n - 2) \cdot \sum (L_i - \bar{L})^2\right]} \quad \text{(dB/km)} \quad (39)\]

Where:

\(n\) – Number of samples
\( \gamma_i \) – The attenuation measured by the \( i \)-th link

\( \hat{\gamma}_i \) – The attenuation estimated by the linear approximation for the \( i \)-th link

\( L_i \) - Length of the \( i \)-th link

\( \bar{L} \) – Average length of the links

Based on Eq. (34), uncertainty in estimating attenuation leads to uncertainty in the LWC estimation which is given by (Ku, 1966):

\[
\Delta LWC = \Delta \hat{\gamma}_i \cdot \Phi^{-1} \quad \text{(gr/m}^3\text{)}
\]  

(40)

In this study, the uncertainty caused due to temperature variations was neglected while deriving Eq. (40). The difference between the temperature measurements of the different gauges (with an instrument error of 0.1 °C) in the observed area was between 1 and 2 °C at the time of the microwave system measurement. This uncertainty creates LWC variations an order of magnitude less than the uncertainty created from the effective fog induced attenuation using the model (Rec. ITU-R P.840-4, 2009).

### 2.1.3B Wet antenna

The estimation of attenuation resulting from a possible wet antenna, \( A_w \), was carried out by evaluating the \( y \)-intercept of the line (which represents a theoretical distance of 0 between the antennas). In order to estimate the error in this value the calculation for constant term error in a linear approximation was used (Kenney and Keeping, 1962):

\[
\Delta \hat{A}_w = \sqrt{\frac{1}{\sum (\gamma_i - \hat{\gamma}_i)^2 \sum L_i^2 \cdot [\Phi(n-2) \cdot \sum (L_i - \bar{L})^2]^{-1}} \quad \text{(dB)}
\]  

(41)

### 2.1.3C Visibility estimate bounds

An upper and lower rough bound for the visibility assessment was set based on the contribution from two factors – the LWC uncertainty derived directly from the link measurements, and from an assumed uncertainty which was taken to be 30% for the warm-fog visibility parameterization. Prior research (Gultepe et al., 2006) has shown that the uncertainty estimation for Eq. (37) is about 29%, where the uncertainties in LWC and the droplet number concentration- \( N_D \) taken into account in creating this
estimate were 15% and 30% respectively, and under the assumption that in visibility, fractional uncertainty is the sum of the fractional uncertainties in LWC and the parameter \( N_D \). The formula was derived based on LWC in the range between 0.005 and 0.5 gr/m\(^3\) and for values of \( N_D \) between 1 and about 400 (cm\(^3\)). Notably, the estimation of \( N_D \) in this work was derived from the temperature (Eq. (38)), which may create additional disparities in estimating this parameter (Gultepe and Isaac, 2004; Gultepe et al., 2006) due to dependency on other physical and dynamic factors (e.g., nucleation and turbulence, respectively). To reach the visibility range presented here, first, the maximum and minimum values of LWC observed by the links were calculated, according to the uncertainty values associated with calculating LWC from attenuation measurements (Eq. (40)). Then, the visibility range was calculated from these minimum and maximum LWC values using Eq. (37) and assuming a 30% uncertainty estimate related to this calculation (Gultepe et al., 2006). Based on these assumptions, in this work, the estimated visibility range is a measure of an order of magnitude. Adding information about the microphysical structure of the fog based, for example, on side information taken by proprietary instruments (e.g. direct measurement of \( N_D \)) will reduce the uncertainty in the visibility estimate, which is a matter for future research.

### 2.2 Water vapor

#### 2.2.1 Estimating humidity through wireless communication networks measurements

In this part of the research, the discussion is restricted to weather conditions which exclude precipitation, fog or clouds along the link propagation path.

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

\[
\Gamma = A_v + A_o + \tilde{N}_{oise} \quad \text{(dB/km)}
\]  

(42)

Where:

\( A_v \): The specific attenuation due to water vapor.

\( A_o \): The specific attenuation due to dry air.
\( \text{\textit{Noise}} \): All other signal perturbations created as a result of other than water vapor.

It should be noted that this model (Rec. ITU-R P.676-6, 2005) takes into account also the effects of dry air (Oxygen) and corrects for them. However, assuming moist air, \( A_o \) is one order of magnitude lower comparing to \( A_v \) at frequencies of \(~22\ \text{GHz}\), and therefore the signal loss is caused predominantly by the water vapor (See also Fig. 18). Hence, according to equations (26) and (42):

\[
A_v = 0.1820 f N''(p, p, f, T) + A_o + \text{\textit{Noise}} \quad (\text{dB/km})
\]

Where:

\( f \)- The link's frequency (GHz).

\( N'' = N''(p, f, T, \rho) \) - The imaginary part of the complex refractivity measured in N units, a function of the pressure \( p(\text{hPa}) \), temperature \( T(\degree\text{C}) \) and the water vapor density \( \rho(\text{g/m}^3) \).

While:

\[
N'' = \sum S_i F_i + N''_D \quad (\text{N units})
\]

\( S_i = S_i(p, T) \): The strength of the \( i \)-th line (KHz).

\( F_i = F_i(p, T, \rho, f) \): 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 vapor, the sum extends over all lines up to 1000 GHz. The detailed expression of the functions of \( N'' \) is described in the literature (Liebe, 1985; Rec. ITU-R P.676-6, 2005).

In this work, The RSL value, chosen as the point of reference, was set for each link by subtracting the attenuation created by a typical moist air in the area over several weeks based on prior humidity data obtained from the IMS from the median RSL measurement of these weeks.

Consequently, given the atmospheric temperature, pressure and the link’s frequency, the water vapor density- \( \rho \ (\text{g/m}^3) \) is estimated numerically through Eq. (43), using the known relation between \( N'' \) and \( \rho \).
2.2.2 Estimating humidity from surface station data

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

$$e_s = 6.112 \exp \left( \frac{17.67T}{T+243.5} \right) \quad \text{(hPa)} \quad (45)$$

$$e = \rho \frac{T + 273.15}{216.7} \quad \text{(hPa)} \quad (46)$$

$$\frac{e}{e_s} \times 100\% = RH \quad \% \quad (47)$$

$e_s$ - The saturation water vapor pressure (hPa).

$e$ - The water vapor partial pressure (hPa).

$T$ - The temperature (°C).

$\rho$ - The water vapor density (g/m$^3$).

RH - The relative humidity (%).

Hence:

$$\rho = 1324.45 \times \frac{RH}{100\%} \times \frac{\exp \left( \frac{17.67T}{T+243.5} \right)}{T + 273.15} \quad \frac{g}{m^3} \quad (48)$$

2.2.3 Statistical tests

The correlation between absolute humidity values calculated using the method described, and those measured using a regular humidity gauge was examined. 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:

$$\text{RMSD (g/m}^3) = \sqrt{\frac{\sum_{i=1}^{N} (\rho_{m} - \rho_{gi})^2}{N}} \quad (49)$$
\( \rho_{m} \) - The \( i-th \) water vapor density measurement as measured using the microwave link (g/m\(^3\)).

\( \rho_{g} \) - The \( i-th \) water vapor density measurement as measured using the humidity gauge (g/m\(^3\)).

N - Number of samples.

The humidity measurements taken via the microwave link were calculated from a signal sampled at 03:00 a.m. Local Time (LT). 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.

### 2.3 Rainfall Intensity Estimation Using MLs

Of the different atmospheric phenomena discussed, the dominant cause of signal attenuation in the given frequency range (6 to 40 GHz) is precipitation, and its effect is approximately an order of magnitude greater with respect to the other phenomena (Fig. 1).

In order to determine the base line level of the microwave measurements the median no-rainfall RSL measurements were chosen separately for each link over a no rain period (of at least two hours) prior to the onset of the event (Overeem et al., 2011). Then, these measurements were subtracted from those acquired during the rainfall event itself. Occasional negative values were clipped to zero. Rain wetting the outer cover of the microwave units creates considerable signal loss in addition to the path-integrated rainfall-induced attenuation. Hence, the total attenuation measured by a link- \( A_M \) is predominantly comprised of the path-integrated attenuation- \( A_P \) and the wet antenna attenuation \( A_w \) (e.g. Zinevich et al., 2010):

\[
A_M = A_P + A_w + \tilde{\text{Noise}} \quad (dB)
\]

\( \tilde{\text{Noise}} \): All other signal perturbations created as a result of other than rain phenomena.

Precipitation induced attenuation can be described by Eq. (29) from which the value of the average precipitation, \( R_L \), along a link of length \( L \) can be derived as follows:
\[ R_L = \left( \frac{A_p}{a} \right)^{1/b} \quad (mm/hr) \] (51)

### 2.3.1 Wet antenna attenuation

A correction for the wet antenna effect can be performed using the known relation (Zinevich, 2010)

\[ A_w = A_M - \min \left\{ \alpha (1 - e^{\beta A_M/L}) \right\} (dB) \] (52)

Where \( A_w \) (dB) is the approximated attenuation caused by the wet antenna and \( L \) is link length (km). The values of the parameters \( \alpha \) and \( \beta \) were taken from literature (Zinevich, 2010). Leijnse et al. 2008 have shown that attenuation resulting from wet antenna is mostly independent on frequency in the range of 18-23 GHz used in this work for rainfall monitoring.

### 2.3.2 Estimating path integrated rainfall

Given measurements of the RSL, and transmission levels, the rainfall induced attenuation can be derived and hence the requested path averaged rain rate- \( \hat{R}_L \). Consequently, assuming uniform distribution of rain intensities along a link:

\[ \hat{R}_L = \left( \frac{A_M - A_w}{L_a} \right)^{1/b} \quad (mm/hr) \] (53)
CHAPTER III

RESULTS

3.1 FOG

The research was centered on two extreme fog events that took place in Israel. In both cases visibility dropped to or below several tens of meters, and the events continued throughout the night and the following morning. The thick fog developed to a scale of a few tens of km, covered the southern and central coastal plain and lowland regions of Israel as well as parts of the Sinai Peninsula in Egypt as illustrated by the satellite images (Fig. 6a, Fig. 9a). The images were produced using CAPSAT- the Clouds-Aerosols-Precipitation Satellite Analysis Tool (Lensky and Rosenfeld, 2008) based on infrared measurements from a combination of the SEVIRI (spanning enhanced visible and infrared imager) channels (IR3.9, IR10.8 and IR12.0). The extremely low visibility conditions during these fog events led to disruption, cancellations and delays in the flight schedule for Ben Gurion international airport.

The analysis focuses on the central western coastal region (Tel Aviv city- Ben Gurion airport area) where several means for measuring the phenomenon exist. The microwave data used were gathered from the tens of commercial MLs operating at around the 38 GHz frequency range in the area that are located in the vicinity of the specialized measuring equipment. The links are installed at elevations between 5 and 90 m Above Sea Level (ASL) on towers that range from 5 to 100 m Above Ground Level (AGL) and span in length from 100 m to ~3.5 km. Each one of the links provides one measurement per day at a 0.1dB resolution. The measurements are taken instantaneously and simultaneously across all of the links in the system at a prescribed time as reported by the cellular providers. The communication companies technically modify the system routinely based upon to their needs. These changes include e.g. the number of MLs operating in a given frequency range. Thus, the specific links used were different in each case studied, in accordance to their availability at the 38 GHz band. During both events, no rainfall, sleet or snow were measured in the examined area according to the observations of the surface stations.
3.1.1 Case 1: 9-10 December 2005

Between the late evening of 9 December 2005 and the morning hours of the next day, a heavy fog front passing through central Israel was recorded by different observation techniques found in the area. At the surface, a ridge from the west with weak westerlies (and a long fetch over the Mediterranean Sea) was accompanied by a deep ridge aloft, which was causing significant subsidence.

Since the microwave system that provided the data used for this research recorded measurements around 01:30 Universal Time Coordinated (UTC), this time frame was used as the focal point for the research.

Figure 6a shows the regional satellite image acquired during the event (01:27 UTC). Figure 6b indicates the location of the different measuring means in the region as well as the deployment of the ML system. According to the measurements of the three regional stations in the observed area (Fig. 6b), the Relative Humidity (RH), as measured between 01:00 and 02:00 UTC, ranged between 97%-100%. (with temperature of around +13 °C and wind speed of ~1-2.5 m/s).

Fig. 6. The observed area. (a) The image was taken by Meteosat Second Generation (MSG) at 01:27 UTC on 10 December 2005. The wide fog front (tens of km in scale) is indicated in the image in white. The square (red) indicates the area of focus in this research.

(b) Map of the MLs and measurement instruments in the observed area. The 88 MLs at the site are deployed over 47 physical paths and span an area of 5 x 6 km². Three transmissometers, and a professional human observer are located at Ben Gurion airport (41 m ASL). The three meteorological ground stations (5-35
m ASL) are indicated by asterisks. An additional human observer is located at the Beit Dagan ground station (35 m ASL).

Visibility assessments were acquired by two human observers located at the Beit Dagan station, and at the Ben Gurion airport (Fig. 7a). The Meteorological Optical Range (MOR) measurements (WMO, 2008) were taken by the three transmissometers located at the airport (Fig. 7b). According to these different observation techniques limited visibility due to fog was detected between 22:00 and 07:00 UTC (of 9-10 December, respectively), dropping to a minimum of 50 m (transmissometers) and 100 m (Ben Gurion observer).

Fig. 7. Visibility assessments. The assessments were carried out between the hours of 15:00 UTC on 9 December, and 12:00 UTC on 10 December, 2005, respectively.

(a). Visibility assessments as registered by the human observer at the Beit Dagan meteorological station and Ben Gurion airport. Assessments were made once every 3 hours by the observer located at Beit Dagan and once an hour by the Ben Gurion observer. Fog was detected between 00:00 to 06:00-07:00 UTC.

(b). MOR measurements taken by three transmissometers located at Ben Gurion airport. The instruments are arrayed over three separate 50 m visual paths at an elevation of 2.5m AGL (The figure is based on instantaneous measurements at 10 minute intervals). According to these instruments, fog was detected starting from around 22:00 till 07:00 UTC of the following morning.
**Fog identification and intensity estimation using MLs measurements**

88 MLs in the observed region were used during the event, deployed over 47 different paths, covering an area of approximately 5 by 6 km² (Fig. 6b). Each of the links provided one measurement every 24 hours (01:30 UTC). The attenuation measurements from the foggy night were compared to those taken on a humid night without fog (according to the records from the different specialized measuring instruments).

**Fog Identification:** During the foggy night, on 10 December 2005, an RSL drop was recorded by numerous MLs, of different lengths, located in the area (during RH >95% conditions). Figure 8a presents the attenuation measurements from the different MLs, as a function of link length. Figure 8b shows the measurements which were acquired during a humid night (15 December) without fog (a RH of ~65%, ~90% and 85% was measured by the Tel Aviv coast, central Tel Aviv and Beit Dagan surface stations, respectively, around 01:30 UTC). The additional attenuation measured by the links on the foggy night with respect to the humid night is apparent. During the foggy night the Pearson correlation coefficient between observed attenuation to link length was found to be \( r = 0.55 \) (with P-value < 0.01 (Neter et al., 1996), based on 88 data points). Given the high RH of ~95% and the additional attenuation observed by the multiple MLs, fog was identified as being present in the area.

![Microwave attenuation measurements](image)

Fig. 8: Microwave attenuation measurements. The attenuation measurements, as measured by the MLs system on a foggy (10 December) night (a) and during a humid night (15 December) without fog (b). Every point represents a measurement from a single link, taken around 01:30 UTC. The linear fit approximations of the measurement sets are listed at the top of each panel. The slope of the graph in (a) represents the effective attenuation measured in the fog patch (based on 88 microwave samples), where the y-axis intercept represents the estimated attenuation as a result of antenna wetness. The slope of the graph generated for the non-foggy night, as well as the y-intercept tend to zero (based on 68 samples acquired according to the availability of RSL data from the system during that night).
Estimating liquid water content and visibility: The estimate of the effective fog induced attenuation - \( \hat{a}_f \), is given by the slope of the resulting plot (Fig. 8a). The estimate for the wet antenna component, \( \hat{A}_w \), is given by the constant term.

A similar plot was created for the non foggy night, where the slope of the resulting graph tends to zero (Fig. 8b).

Given, \( \hat{a}_f \), the temperature and the MLs frequency the value for the LWC was calculated using Eq. (34). Then, minimum and maximum bounds on the range of visibility were derived using Eqs. (37) to (40). The resulting values were \( 0.7 \pm 0.1 \) gr/m\(^3\) and 30 to 70 m, respectively.

Table 1 lists the results of the ML measurements and the visibility assessments received, during the same time period, from the different measurement means. The visibility assessments derived from the ML measurements are of a similar order of magnitude as the assessments from the specialized measurement equipment.

Table 1. Comparison of the visibility assessments and microwave measurements with the specialized measurement instruments (10 December 2005). The observations listed in the table were made over the same time when the ML measurements were taken, where the hour / time period indicated in parentheses (UTC) in each column is the period during which the measurement was taken by each mean (the visibility range based on ML measurements indicates the upper and lower bound for the estimate). Temperature and RH measurements were acquired (at 10-minute intervals) by the three ground stations between 01:20 and 01:40 UTC. The Ben Gurion and Beit Dagan observers provided visibility estimates once an hour and once every 3 hours, respectively. The MOR measurements are based on 10-minute intervals as acquired by each of the three transmissometers. The LWC, wet antenna and fog induced attenuation values measured by the MLs, are also listed.

<table>
<thead>
<tr>
<th>RH [%]</th>
<th>T [ºC]</th>
<th>( \hat{A}_w ) [dB]</th>
<th>( \hat{a}_f ) [dB/km]</th>
<th>LWC [gr/m(^3)]</th>
<th>MLs Vis max/min bounds [m]</th>
<th>MOR [m]</th>
<th>B. Gurion Observer [m]</th>
<th>B. Dagan Observer [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>97-100</td>
<td>12-13.5</td>
<td>0.62±0.15</td>
<td>0.63±0.1</td>
<td>0.7±0.1</td>
<td>30-70</td>
<td>~50</td>
<td>100-400</td>
<td>500-900</td>
</tr>
</tbody>
</table>

(01:30 h) (01:20-01:40 h) (01:00-02:00 h) (00:00-03:00 h)
3.1.2 Case 2: 15-16 November 2010

Starting on the evening of 15 November 2010, a heavy fog front began developing and expanding along the area of Israel's Mediterranean coast. At the surface, a Red Sea Trough with a central axis was moving eastward, allowing for northwesterly flow from the Mediterranean Sea to move into the coastal area. Aloft, a deep ridge was moving eastward. Fog conditions continued through the morning hours of 16 November 2010.

The satellite image shows the wide region affected during this fog event (Fig. 9a), as well as the site discussed here, which is detailed in the map (Fig. 9b) adjacent to the image.

Fig. 9. The observed area. (a). The image was taken by the MSG satellite on 16 November 2010, 00:34 UTC. The fog is indicated in white and the study area by the red square. (b). Map of the MLs and measurement instruments in the observed area. The 58 MLs in the area are deployed over 39 physical paths and spread across an area of about $15 \times 10$ km. Measurements are obtained once every 24 hours at 22:00 UTC (satellite Images which were acquired around this hour during the event did not provide clear indication for the fog in the region due to middle and high altitude cloud cover that obstructed the satellite line of sight to the ground, see Fig. 12). There are three transmissometers located at Ben Gurion airport (41m ASL) as well as a human observer. Another human observer, as well as a scatterometer are located at the Beit Dagan ground station (35m ASL).
The microwave system that provided the data used for this research recorded measurements at 22:00 UTC and hence this time frame was used as the focal point for the research.

Let us focus on the area of Beit Dagan station (Fig. 9b) in the proximity of MLs where the measured humidity was 90% - 97% between 21:30 and 22:30 UTC (with a temperature range of 18.5 -19 °C and wind speed of ~1 to ~3 m/s). Figure 10a shows the visibility results registered by the professional human observers located at Beit Dagan station and Ben Gurion airport. The graphs described in Fig. 10b are based on Runway Visual Range (RVR) measurements (AMS, 2000) of three transmissometers located at the airport. In addition, MOR measurements of a scattermeter found at Beit Dagan which was available during this event, are also presented.

According to all of these observations, between 21:30 and 07:30 UTC of 15-16 November 2010 severe visibility limitations were observed, decreasing to the order of a few tens of meters and less (between 22:00 and 01:00).

Fig. 10. Visibility and RVR measurements. The observations were taken between November 15 and November 16, 2010, between 20:00 and 10:00 UTC the following day. (a). Visibility assessments as registered by the human observers (at the Ben Gurion and Beit Dagan station). Observations were taken once an hour by each observer (the Beit Dagan observer estimates between 22:00 to 01:00 UTC of several meters to 100 m, were plotted as 50 m during this time frame). Also depicted are MOR measurements at 1 minute intervals which were acquired by a scattermeter located in Beit Dagan. (b). RVR measurements taken by the three transmissometers deployed at the airport over three different physical paths (the plot is based on instantaneous measurements at 5 minute intervals).
Fog identification and intensity estimation using MLs measurements

58 MLs deployed in the observed region over 39 separate paths were used during the event (Fig. 9b). The system is spread across an area of approximately 10 x 15 km², and captures one instantaneous measurement from each link every night (at 22:00 UTC). The measurements taken on the foggy night to those taken during a humid night at the same hour were compared.

**Fog Identification:** During the foggy night (15 November), an RSL drop was recorded by multiple MLs located in the area (at RH of ~95%). The attenuation measurements from the ML network in the area during this night are presented in Fig. 11a. The correlation between observed attenuation and link length during the foggy night was r =0.57 (P-value < 0.01, based on 58 data points). Figure 11b shows the measurements taken on a humid night (10 November) without fog (RH ~87% around 22:00, according to Beit Dagan station).

Given the high RH of ~95% and the additional attenuation observed by the multiple MLs fog was identified as being present in the area.

![Fig. 11. Microwave attenuation measurements. Observations taken on the foggy night, 15 November 2010 (a), and those taken on the humid night, 10 November 2010 (b). Each point represents a measurement from a single link, taken simultaneously at 22:00 UTC. The linear fit approximations of the measurement sets for each night are listed at the top of each panel.](image)

**Estimating liquid water content and visibility:** The LWC value measured, using the same procedure described previously, was found to be 0.68 ± 0.15 gr/m³. Accordingly, the range of visibility was assessed to be 30 to 70 m.
Table 2 lists the ML measurements and the different visibility assessments as measured around 22:00 UTC by the different measurement means.

**Table 2: Comparison of the visibility assessments and microwave measurements with the specialized measurement instruments (15 November 2010).** The observations listed in the table were made over the same time when ML measurements were taken, where the hour / time period indicated in parentheses (UTC) in each column is the period during which the measurement was taken by each measuring mean. Temperature and RH measurements were acquired by the Beit Dagan ground station between 21:50 and 22:10 UTC (at 10-minute intervals). Observers provided visibility estimates once an hour. The MOR measurements were taken by the scattermeter at Beit Dagan, in 1 minute intervals. The notation “Med” indicates the median value.

<table>
<thead>
<tr>
<th>RH [%]</th>
<th>T [°C]</th>
<th>$A_w$ [dB]</th>
<th>$a_{f}$ [dB/km]</th>
<th>LWC [gr/m³]</th>
<th>MLs Vis max/min bounds [m]</th>
<th>MOR [m] (B. Dagan)</th>
<th>B. Gurion Observer [m]</th>
<th>B. Dagan Observer [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-96</td>
<td>19</td>
<td>0.21±0.15</td>
<td>0.53±0.1</td>
<td>0.68±0.15</td>
<td>30- 70</td>
<td>30 to 950</td>
<td>50-500</td>
<td>Several meters-100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(22:00 h)</td>
<td>(21:50-22:10 h)</td>
<td>(22:00-23:00 h)</td>
</tr>
</tbody>
</table>

It should be noted that it was not possible to acquire a clear image of the fog utilizing the satellites observations around 22:00 UTC (of 15 November) due to middle and high altitude cloud cover that obstructed the satellite line of sight to the ground, essentially partly hiding the ground level fog from the satellite's vantage point.

Figure 12 exemplifies this limitation of the satellite system in providing indication for the fog event. On the other hand, as shown in Figure 10 and Table 2, particularly during this time frame the intensity of the event reached its peak. As a result, the numerous MLs deployed in the area have also detected heavy fog (Fig. 11a) and thus demonstrating the potential advantage of the microwave system over satellites to provide direct ground level observations.
Fig. 12. Fog obscured by clouds. The satellite image (MSG) was taken at 22:00 UTC on the 15 November 2010. The middle and high level cloud cover, indicated in red colors (denoted by white arrow in the figure) partly obscure the fog from the satellite vantage point.
3.2 **WATER VAPOR**

3.2.1 MLs vs. conventional humidity gauge measurements

Humidity observations, based on commercial microwave links data, were made in several different locations in Israel (Fig. 13), and at several different times. The results presented here (Figs. 14-17) are for Haifa Bay area, northern Israel and Ramla region, central Israel. The observations of these MLs were made during November 2005, May 2008 and September 2007, April-May 2007, respectively.

![Diagram showing regions](image)

**Fig. 13. The examined regions.**

(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 transmitter and receiver are found at heights of 265 and 233 m ASL. The distance from the surface station to a point located in the middle of this wireless link is 7.5 km. The transmitting 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.

(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 station while its transmitting and receiving units are situated 116 and 98 m ASL. The airport surface station is situated at 41 m ASL.

Figures 14-17 present results for daily variations in the absolute moisture which were calculated using data obtained from the wireless communication network (dark), as compared to in-situ measurements (bright), over a month. The system from which the data were collected captures a single signal every 24 hours at 03:00 a.m. LT. 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. LT (according to close by surface stations), were excluded.

![Water Vapour Density - North Israel 11/2005](image)

**Fig. 14. Northern Israel.** 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. 13a). 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/m³).
Fig. 15. 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. 16. Central Israel. The measurements were taken during the month of September 2007 (25 days, according to the availability of the microwave and meteorological data). 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$^3$).
The measurements were taken between 20 April and 20 May 2007, excluding 2 days (5 and 19 May) when unphysical attenuation, i.e. that is greater than the typical moist air attenuation, was observed. 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 results show a persuasive match between the conventional technique and the microwave based method, the correlation coefficient between the time series in the four presented cases is between 0.9 and 0.82. In all cases, the p value is less than 0.05. The RMSD were found to be between 1.8 g/m$^3$ 3.4 g/m$^3$. The presented results are examples of cases, demonstrating relatively good agreements. Similar comparisons were performed for other links and other time slots showing correlations in the range of 0.5–0.9.

The largest difference between the traditional and the novel method measurements appears in Fig. 17, 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 RH by a radiosonde launched at 03:00 a.m. LT from Beit Dagan (Fig. 13b), a few km away from the microwave link, at an altitude of 95 m ASL was 97%). Additionally, according to a human observer located at Ben Gurion airport, the visibility during this night decreased down to the range of 1000- 2000 m (between 00:00 to 10:00 a.m. LT). Thus, the reason for the additional attenuation observed by the microwave link (expressed by a higher moisture level) might be due to local fog/ moist smog (David et al., 2012a, 2013a) or due to a
possible condensation of a thin layer of liquid water (dew) on the outside cover of the microwave antennas (Henning and Stanton, 1996). When excluding the 6 May measurement, the correlation increases to 0.85 and the RMSD decreases to 2.9 \((g/m^3)\). It should also be noted that two measurements taken on 5 and 19 May were excluded. During these nights Beit Gamliel surface station (see Fig. 13b), measured light amounts of precipitation (~0.1 mm) indicating the possibility of the creation of dew. It is, therefore, possible that the increased attenuation in this case, was also caused as a result of this phenomenon or as a result of other interference such as wind moving the transmitter or receiver (Leijnse et al., 2007a). Notably, during 23 April and 20 May 2007 the moisture measurements obtained by the microwave system were calculated to be around 0 gr/m\(^3\). This value is not reasonable and further research is required to identify the sources of these perturbations. The different components of measurement errors are detailed in Chapter IV.

### 3.2.2 Uncertainties

Rain, fog, snow and clouds create additional attenuation in relation to that caused by water vapor. One of the research challenges one is faced with is separating the effects of different attenuation sources. Since the purpose of the current work is to prove feasibility, at this stage, the technique was limited to periods where none of the aforementioned phenomena exist along the link line-of-sight.

In order to calculate the water vapor density the model used (Rec. ITU-R P.676-6, 2005; Liebe, 1985) takes into account the barometric pressure, temperature and the microwave attenuation.

The uncertainty in measuring temperature and pressure are of the magnitude of 1 degrees Celsius, and 1mb, 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. A dominant uncertainty affecting the absolute humidity calculation is that of the attenuation quantization error. The uncertainty, as calculated here using the model (Rec. ITU-R P.676-6, 2005), was derived based on the quantization error- \(\Delta q\) while the latter is given per link, and so, the average calculated error per unit of distance changes with respect to link length, \(L\).

\[
\Delta \rho = f(p,T,f,\Delta q)/L \quad (g/m^3)
\]  

(54)
Given a quantization error of 0.1 dB as of the wireless system used here, the uncertainty in evaluating attenuation based on the model (Rec. ITU-R P.676-6, 2005) was found to be ± 0.025 dB/km for a typical 4 km long link (a length which is of the same 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/m³. In the case of an 11 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/m³.

The estimated uncertainty in measuring humidity with regular humidity gauges was calculated according the following formula, depending on the relative humidity and the temperature (based on Eq. (48)):

$$\Delta p = 1324.45 \times \frac{\Delta RH}{100} \times \exp \left( \frac{17.67T}{T + 243.5} \right) \frac{1}{T + 273.15}$$ (g/m³) (55)

The resulting uncertainty was found to be in the range of 0.3 to 0.5 g/m³, while the error in measuring RH was taken to be 3% and a typical temperature range of 10- 20 °C , representative for the cases discussed here, was taken into account.

Dry air effect on attenuation is one order of magnitude lower than that of water vapor 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/m³ and a sea level pressure). Figure 18 presents the microwave attenuation induced by atmospheric gases (Rec. ITU-R P.676-6, 2005). Notably, around the 22.2 GHz absorption line (Van Vleck, 1947a) the humidity induced attenuation is an order of magnitude higher than the dry air effect (However, the algorithm takes into account also the effects of dry air, and corrects for them).
Fig. 18: Specific attenuation due to atmospheric gases. Blue line signifies the water vapor induced attenuation. Red line- attenuation due to dry air. Black line- the total attenuation due to both components. Notably, around 22 GHz- (i.e. around the absorption line we focused on during this part of research) the attenuation as a result of water vapor is one order of magnitude higher comparing to the dry air effect. The attenuations were calculated given a barometric pressure of 1013 mb, temperature of 15 °C, and water vapor density of 7.5 g/m³ (the figure is taken from Rec. ITU-R P.676-6, 2005).

Additional discussion concerning additional different sources of uncertainty in the MLs measurements is found in the sequel (section 4.1).
3.3 Rainfall Monitoring in Dry Climate Regions

3.3.1 The Dead Sea and north Negev regions

The Negev desert, constitutes the southern half of Israel, is an arid climate region extending between the latitudes of 29° North and 31°20 North (Kidron, 2000; Jacobs et al., 2002; Kahana et al., 2002). The climate found in the area of the Dead sea (which borders with the northeast part of the Negev) spans from arid, in the south part and near its shores, to Mediterranean, semi arid climate, in the north (Cohen and Laronne, 2005; Dayan and Morin, 2006).

Severe convection generates heavy precipitation in these regions while two dominant synoptic systems account for most of the major rainfall events (Krichak et al., 2000; Kahana et al., 2002; Dayan and Morin, 2006). One of these is the Red Sea trough - a tropical synoptic scale system. This barometric trough is accompanied by an upper-level trough which develops over Egypt, providing favorable conditions for the development of severe convective storms. Alpert et al. (2004) have shown that the frequency of Red Sea troughs has doubled over the last 5 decades. The second synoptic system contributing to rainfall in the area is a Syrian Low - an intense Mediterranean cyclone which is centered over Syria.

In the cases demonstrated below it is shown that the radar system covers the middle of the country, while the arid climate study areas, are in the south. As a result, due to the curvature of the Earth and the radar beam transmission angle, the radar precipitation measurements over these areas are distant from the surface at an elevation of about 2000 m above ground level in the case of the north Negev region. In the southern Dead Sea area, in addition to the aforementioned problem, the radar beam, and particularly the one that is transmitted at the lowest elevation angle (which is targeted at providing precipitation measurements from elevations closer to the ground) is disrupted by the regional topography. The data, from the minimal elevation, acquired in this case, are actually measured at an altitude of about 1500 meters above ground. Particularly in dry climate regions, observations from these considerable elevations may not reflect the near-surface rainfall well not only due to the aforementioned radar measuring uncertainties (section 1.1.3), but also due to relatively large evaporation of the rain drops before reaching the surface (e.g.
As a result of these conditions, precision of these QPE is doubtful.

### 3.3.2 Results

Three case-studies are presented. Two rainfall events that occurred in the arid region of the southern Judean desert and in the northern part of the Negev. The 3rd case-study is based on a rainfall event occurred in northern Israel over an area of complex topography. The microwave system, spread across the tested regions, provides minimal and maximal measurements per 15 minute intervals for each link. Accordingly, the maximal and minimal rainfall intensities were derived based on these measurements (Eq. (53)). The microwave link values represent the average measurement of several links that are routed over the same physical path. The attenuation measurements of the links were related to rainfall only when attenuation was simultaneously recorded on several links over the same propagation path.

**Case 1: 24-25 October 2008**

There are 32 MLs deployed in the first examined region of the southern Judean desert. The system's frequency range is 17-19 GHz with a quantization error of 0.1dB. These links span 6 to 26 kms in length, across an area of approximately 60x30 km². All links are installed between 10 and 50 meters above ground level and are spread across seven different physical paths (transmitting more than one link over the same physical path is possible by varying link frequency and polarization). The results presented for this case study are derived from 29 of the 32 MLs found in the region (In some cases, some links were not employed due to a technical malfunction or lack of data for the particular link). Also presented are measurements from 6 Israel Meteorological Service (IMS) rain gauges located at the examined area. On the night between 24 and 25 October 2008, heavy precipitation fell in the Judean desert and the Negev over short periods of time. Cold air at high altitude and the entrance of humidity from Jordan in the east, created a well-developed convective cloud, covering the northeastern Negev, and southern Judean desert (Fig. 19.A)
The IMS rain gauges which are deployed in the area, as well as the network of microwave links are depicted in Fig. 19.A. A convective cell (green) can be seen in the Tamar Fort region. The rainfall in this area was detected by the microwave links in the vicinity long (at least 50 minutes) before the rain gauges in the area as can be seen in Fig. 19 (B-E). The cell did not pass over all the specific point-locations of the rain gauges in the region.

Among the rain gauges: the Sdom gauge was the first to measure precipitation only at 21:50 LT. The Rotem plain rain gauge – did not indicate precipitation at all while many of the microwave links located at the area indicated precipitation.

As can be seen from the microwave link measurements (Fig. 19.B-C) the cloud movement, in this case, was from south to north. As a result the relatively southern links were the first to measure precipitation as early as 21:00 LT. Finally, the northernmost links, of Beit Yatir- Shima and Beit Yatir-Arad physical paths, detected precipitation.
Fig. 19. Precipitation measurements over the Dead Sea region. The microwave links and rain gauges located in the arid area are superimposed over a magnified radar image (A) which was acquired at 21:00 LT. (B)-(E): Maximal (B) and minimal (C) intensities of precipitation as measured by the microwave links, compared to that measured by the IMS' rain gauges (Fig. (D) and (E)) located in the area. The Rotem plain rain gauge, not depicted here, did not measure precipitation at all. The indicated time represents the first detection of precipitation. The color of each convective cell (Fig. 19A) indicates the rainfall intensity according to the scale found to the right of each image.
A simulation was carried out in order to evaluate the effectiveness of the MLs in capturing the precipitation in comparison to the rain gauges across the study region, as illustrated in Fig. 20. The locations of the precipitation stations and microwave links in the area were mapped. Random circles of a 5 km radius were inserted into the simulation area to represent the convective cells in the region.

![Map of the study area](image)

**Figure 20:** The study area. The blue circles signify convective cells which were randomly inserted into the simulated tested region.

In the simulation the cases where the location of a convective cell corresponded with a microwave link below it, were counted. Where several links corresponded with a single convective cell – the occurrence was counted only once.

Similarly, all cases where a convective cell was located above the rain gauges were enumerated. The simulation was run for 10,000 cases in which 10,000 convective cells were randomly positioned above the simulation area. The results showed that the probability of detecting a convective cell with the microwave links located in this region was 3.6 times greater than the probability of detecting one using a rain gauge: 26.6% against 7.3%, respectively.
Case 2: 17-18 January 2010

On January 17-18, 2010, the Negev, Arava (and Sinai) regions experienced relatively high levels of precipitation. Several IMS rain gauges deployed in the region measured rainfall levels of 30-80 mm that, in some cases, equaled the entire yearly average for the region. This event was generated due to a cold air surge in the middle atmospheric layer in conjunction with an equatorial moisture layer below which was advected to the region from central Africa by the subtropic jet stream (Ziv, 2001).

Figure 21 presents the radar image acquired at 19:00 LT during January 17.

![IMS radar image](image)

Fig. 21. IMS radar image (January 17, 19:00 LT). The study area is marked by a circle. The radar measurements from this region are taken at an altitude of about 2 km above the ground.

Figure 22 details the study area including the locations of the MLs deployed in the site along with two online Meteorological Service rain gauges at this location. In this case, measurements of 4 microwave links located over 2 different physical paths were used. The lengths of the links ranges between 9.5 and 13.2 kms, and they operate in
the 18-23 GHz frequency range with a quantization error of 0.1dB. Links are installed between 27 and 70 meters above ground level.

Fig. 22. The microwave links in the site at the northern Negev. The physical paths of the 4 links are marked as lines while the two Meteorological Service rain gauges, are denoted by triangles. As a result of the strong rainfall, most of a farm located in the area, was severely damaged. Of some 80,000 m$^2$ of vineyards, only 9,000 m$^2$ remained. The locations of the drainage basins in the area are marked by asterisks.
Figure 23, shows the rain rates as deduced from the MLs (maximum and minimum) along with the rain gauges measurements.

![Graph showing rain rates and times](image)

**Fig. 23.** The maximal and minimal rainfall intensities measured using the MLs compared to the Mitzpe Ramon and Ovda rain gauges readings. The indicated times (in LT) over the plot denote the first detection of precipitation by the microwave links (16:30) and rain gauges (18:10, 18:40, respectively).

As early as 16:30 LT, the two links located between Nafha and Mitzpe Ramon already started indicating low intensity rainfall. Figure 24 presents a radar image which was acquired at the same time where a single convective cell can be seen above the specific location of the event, in the area of Mitzpe Ramon.
Fig. 24: Cloud cells location. An IMS radar image which was acquired at 16:30 LT where a single cloud cell can be seen right above the area of Mitzpe Ramon (denoted by the red arrow). During this time frame no rainfall was measured by any of the rain gauges in the area as opposed to the MLs deployed in this location who have started measuring precipitation in the time frame of between 16:15 to 16:30 LT.

Larger amounts of precipitation can be seen from 18:15 LT, further increasing at 18:15-18:30 LT. Beginning at 18:30, rain is also measured simultaneously on the Nafha – Lavan mountain links, indicating that, during this time slot, rainfall fell over the specific area of the farm located by the links' intersection point (Figure 22). On the other hand, the Mitzpe Ramon rain gauge started measuring precipitation only at 18:10 till 18:30 LT and again at later times while the Ovda gauge started measuring only at 18:40 LT. Other rain gauges, installed at more remote locations (at distances of about 25 to 50 km) from the test site, have started measuring rainfall also only from 18:40 LT or at later times.
Case 3: Microwave links vs. radar measurements from a relatively remote area of complex terrain

An advantage of the MLs over the radar system is demonstrated, based on measurements taken during a rainfall event which took place on 11 December 2010 at the Golan Heights, a volcanic plateau spread over an area of 1040 km² (Yom Tov et al., 1995) located on the eastern side of the north Jordan valley (northeastern Israel, as seen in Fig. 25.A), about 150 km away from the radar's location in central Israel. The topographic heights, in this region, range from ~ 2,200 m in the north to below sea level in the south. In this case, the radar beam that is transmitted at the lowest angle reaches an elevation of about 2000 m above sea level at this location. In addition, during this event, the radar rays were propagating through many Cumulonimbus clouds which were found along the propagation path, across a distance of a few tens of km (Fig. 25.A). As a result of these conditions, the radar system underestimated the actual rain rate over the region. Two microwave links transmitting on the same physical path are located in the area. A rain gauge is located 6.5 km from the northern end of the links (Fig. 25.B).

Fig. 25. The IMS radar image (A) was acquired at 13:00 LT. The radar measurements underestimate the precipitation intensity at the Golan Heights region (the area is marked with an arrow). Rain rates of the order of only ~1 mm/hr were measured by this system over the whole area. The IMS rain gauge and microwave links locations at the Golan Heights region (B). Measurements were taken by 2 different microwave links, located across a single physical path (11.1 km long) found at northeastern Israel. Links are installed, along the topographic slope of the area, between 405 m and 923 m above sea level. The IMS rain gauge is located 6.5 km from the northern end of the links at an elevation of 950 m above sea level.
The rain rate measurements from the microwave system were compared to the radar measurements under the assumption that the rain gauge describes an order of the ground truth in the area examined (Fig. 25.B). Each of these methods provides measurements in different ways: the MLs provide maximum and minimum rain rate measurements every quarter hour. Radar provides measurements of rain rate every five minutes, and the rain gauge measures the amount of rain accumulated in every 10 minute period. Therefore, to allow for a comparison to be made, a common base for the three tools as far as measured time interval, as well as the measured quantity (rain rate) was chosen. Since the links provide a maximum and minimum measurement every 15 minutes, one can deduce that precipitation was continuous in intervals where the minimum and maximum measurements are both greater than zero. During intervals where only a maximum value was observed – one can deduce that the precipitation occurred for a period of less than 15 minutes. To correlate the rain gauge and microwave measurements, the maximum measurements of the links that include measurements of precipitation intervals shorter than 15 minutes were used. I correlated the measurements over a half hour interval, from which the maximum rain gauge and link measurements, respectively, were chosen. The correlation coefficient derived from a Pearson correlation test (Neter et al., 1996), was 0.85 (based on measurements taken between 04:30 and 18:30 LT). The radar QPE from the area were also correlated to the rain gauge measurements, using the same time interval (half hour) and for the same time period (04:30 to 18:30 LT). The maximum reading from the rain gauge every half hour was compared to the maximum radar measurement during that same half hour. The correlation coefficient was 0.2. Then, the intensity measurements were compared. Figure 25.A shows a radar image taken during the storm event at 13:00 LT. Figure 26 presents the rain rate measured during the entire event, by each of the methods, in the observed area. The rain gauge measurements can be seen to fall between the minimum and maximum QPE of the links. On the other hand, the radar measurements underestimated the intensity compared to the rain gauge and observed precipitation rates of ~1 mm/hr during the whole storm event.
Fig. 26. Precipitation measurements- Northern Israel. The minimal and maximal microwave links measurements (in black and blue, respectively) taken on 11 December 2010 between 04:30 to 18:30 LT. The system provides measurements every 15 minutes with a quantization error of 1 dB. System frequency range: 18-19 GHz. Also presented are rain gauge measurements (green) and radar observations (red). Rain gauge measurements can be seen to fall between the minimum and maximum QPE of the links while radar observations are of up to ~1 mm/hr during the entire event.

These results show the great potential of microwave systems to provide reliable rain rate measurements from areas where, at times, the radar system does not provide sufficient response.

The disparities between the links measurements to those of the rain gauge are expected, primary due to spatial variability of the rainfall (Zinevich et al., 2010). The variability in precipitation intensity can be large, even when the correlation between the different measurement instruments is high, and especially in areas with complex topography, as shown, for example, in (Buytaert et al., 2006). A relatively similar variability, then, can also be expected in this case, where the rain gauge is located approximately 6.5 km North East of the end of the links (Fig. 25b).
Despite this limitation, the link measurements and those of the rain gauge resemble each other, and both differ from the radar measurements by an order of magnitude.

An additional source for the disparities observed between the rain gauge and the MLs is due to the different nature of the measurement acquired from the different instruments: the links provided path-averaged measurements of the minimal and maximal intensities which were taken instantly at some point in each of the 15 minute intervals while the gauge's intensity rates were derived based on the amount of liquid water that has accumulated inside the instrument during a 10 minute time interval.

### 3.3.3 Uncertainties

Typical commercial microwave systems, such as the systems used in this part of the research, have a given quantization error ($\Delta q$) of 0.1 or 1 dB per link of a given length. The uncertainty in measuring precipitation for links of typical length between $L=5$ and 15 km, based on the quantization error, is approximated. Given this range of lengths, the estimated uncertainty, $\Delta R$, for measuring precipitation intensity is:

$$
\Delta R = \left(\frac{\Delta q}{L \alpha}\right)^{1/b} \Big|_{L=5,15 \atop \Delta q=0.1,1} = 0.1 - 2.7 \quad (mm/hr)
$$

(56)

The calculation was carried out for links at a frequency of 20 GHz, vertically polarized where $a=0.06898$ and $b=1.0663$ (Rec. ITU-R P.838-2, 2004).

Additional factors affect the system's measurement precision, this issue will be discussed in the sequel (Chapter IV).
CHAPTER IV

DISCUSSION

The challenges in monitoring atmospheric hydrometeors using commercial MLs are mostly due to the fact that system measurements are optimized for communication quality of service, and not for meteorological observations, so factors such as link frequency, temporal resolution or quantization of the measurements are given. The opportunities come, on the other hand, from the availability of many links. These are widely spread across the terrain at relatively high densities and different lengths/heights, observing the atmospheric phenomenon simultaneously at various frequencies.

The ability to monitor rainfall using the commercial microwave links is better than the system's potential of monitoring fog and water vapor, particularly because of the better signal to noise ratio of the effect of precipitation on the system with respect to the effect caused by the other phenomena (Rec. ITU-R P.838-2, 2004; Rec. ITU-R P.676-6, 2005; Rec. ITU-R P.840-4, 2009). Accordingly, of the different microwave systems which were available for this research the most sensitive one was used to examine the monitoring potential of humidity and fog, i.e. a system that provides instant measurements with a magnitude resolution of 0.1 dB and without ATPC. However, this wireless network stores only one datum point per 24h, which may not be satisfying for operational needs. Nevertheless, the system can be configured to store data at shorter time intervals, a matter of technical definition by the cellular companies (David et al., 2009). Due to the strong effect of rainfall on microwave systems it is not surprising that the range of work in this field has concentrated on precipitation observations, including one of the parts of the work presented here (David et al., 2013b). The microwave system, though, has the potential to monitor additional hydrometers, as shown. In a way, there is greater motivation concerning the hydrometers that are not rainfall, due to the immense obstacles that exist for measuring these phenomena on a wide scale, and with low cost, especially in areas where no other instruments exist at all. Prior research (e.g. Fabry, 2006) has shown
that additional tools are required for atmospheric observations, and the method suggested here, with additional development and improvements (Section 4.2.4), has the potential to take the topic a step forward. It should be noted though, that a weakness of the proposed technique is that there are no MLs over the oceans. Therefore, for Numerical Weather Prediction (NWP) models this is a disadvantage, especially in countries where most of the storms originate over the sea (e.g. Israel).

4.1 SOURCES OF ERROR

Identifying the different sources of error and uncertainties for observations that are non-optimal in the first place is essential in order to assure usability of the data.

The primary factors contributing to uncertainty in the measurements include: the given quantization error of the system, antenna wetness, and uncertainty in the baseline used as a reference for the measurements.

Environmental and technical factors are both sources of error in estimating the hydrometeor induced attenuation using MLs (Zinevich et al., 2010). Environmental parameters affecting the uncertainty and particularly the baseline determination include (Leijnse et al., 2007a): mechanical oscillations moving the microwave antennas, such as those caused by winds or, alternately, scatterers found close to the propagation path, e.g. moving tree leaves.

Local temperature and moisture fluctuations resulting from turbulent eddies produce refractive index variations which in turn cause the microwave signals to scintillate.

During times of high relative humidity a thin layer of liquid water (dew) can condensate on the antenna radomes leading to additional signal losses (Henning and Stanton, 1996).

Additionally, while measuring one atmospheric phenomenon, other atmospheric hydrometers may influence the precision of measurement. Thus, during rainfall events, for instance, fluctuations of the water vapor concentrations over time can lead to baseline level variations (David et al., 2009; Zinevich et al., 2010).

Technical factors affecting the base line uncertainty may be ascribed to: temperature variations that affect the analog circuitry of the transmit and receive units and the
given digital quantization error of the commercial MLs.

As far as the wet antenna attenuation as the result of precipitation or condensation on the surface of the external radome during high RH, the sub optimality of the models themselves for describing the induced attenuation of the wet antenna, also contributes to the uncertainty (Zinevich, 2010). When using the precipitation attenuation model (Eq. (53)) uncertainty in the value of parameters $a$ and $b$ as a result of the spatial variability in drop size distribution may also detract from the precision of the measurement (Rincon and Lang, 2002).

An extensive research quantifying and modeling the various sources of perturbations described above using commercial MLs for rainfall monitoring has been recently conducted (Zinevich et al., 2010).

In the current work, the three principal factors of observation uncertainty mentioned were taken into account and thus: wet antenna corrections were carried out in cases where the phenomenon is expected (the cases of precipitation and fog). The uncertainty with respect to the magnitude resolution of the given system in each event was quantified, and the defined baseline for each case was chosen in proximity to the measured events, while using additional meteorological side information (when measuring fog and humidity). This in order to separate between the different phenomena that may take place simultaneously, and in order to rule out, or minimize the effect of factors contributing to uncertainty in the measurements.

In the cases of fog and water vapor, specifically, the goal of this work is to present a proof of concept of the potential ability to monitor these phenomena. Additional research, which is outside the scope of this work, is required to fully model the uncertainties in measurement and is left as a future task.

4.2 SUMMARY AND CONCLUSIONS

4.2.1 Fog

The physical effects of fog on radiation in the microwave range are well studied (e.g. Liebe et al., 1989; Rec. ITU-R P.840-4, 2009; Csurgai-Horváth and Bitó, 2010). The
novelty of the work presented here is the concept of using existing commercial microwave infrastructure, as a fog detection tool, for measuring LWC and deriving visibility assessments.

The impact of dense fog on commercial MLs has recently been demonstrated by the author (David et al., 2012b) for a single fog event (of 15-16 November 2010). This work was published as a discussion paper in the journal *Atmospheric Measurements Techniques Discussions*). However, the liquid water concentrations calculated during that study based on the microwave measurements were found to be beyond acceptable values. The possible reasoning for the inaccurate results obtained is due to the relatively coarse quantization error of the system used (of 1 dB). The calculations were based on only a few MLs while part of them were operating in the relatively low frequency range (of 18-20 GHz) and were, therefore, less sensitive to the direct effects of fog. As opposed, here, a completely new analysis had been conducted and demonstrated for 2 fog events, based on the idea of multi-sensors. A different - more sensitive microwave system was utilized. The MLs used here for the analysis had a measuring resolution ten times greater than the previous one (0.1 dB). Additionally, the research was centered on MLs operating at frequencies around 38GHz – where the sensitivity to fog effects is greater (Rec. ITU-R P.840-4, 2009). Furthermore, the measurements used were taken instantly from tens of different links, of varying length and direction (in contrast to the previous analysis where only maximum and minimum RSL measurements of the system were available and from only several links of that kind). On top of these refinements, the measurements in the current analysis were corrected for wet antenna effects and the RSL which was set as a reference level was also corrected for water vapor induced attenuation (using side information from humidity gauges). Overall, as shown here, these considerable improvements led to more profound results (David et al., 2012a, 2013b). The results obtained show that commercial microwave systems have a potential for fog monitoring, especially in cases of heavy fog that creates severe visibility limitations particularly as it drops to below a few hundreds of meters or to the tens of meters range.

The liquid water content values calculated from the microwave system measurements match similar high values measured directly in field studies, particularly when taking into account the error range in microwave measurements. Values above 0.5 gr/m³
were observed in several studies during periods of dense fog (e.g. Fuzzi et al., 1992; Klemm et al., 2005; Herckes et al., 2007; Gultepe et al., 2009; Niu et al., 2010).

The visibility assessments calculated using the proposed method are of the same order of magnitude as the values measured directly by the different visibility measuring instruments and human observers during the same time period.

A central potential source of error is wetting of the antenna during a fog event. As mentioned previously, the wet antenna effect is well known as a main source of error when measuring rainfall using a ML (e.g. Leijnse et al., 2008; Zinevich et al., 2010). However, in this case the source of possible wettings is different comparing to the case of rainfall since it is resulting from condensation of the atmospheric water vapor due to the high RH. The results suggest that this effect is likely to be considerable also in the case of fog monitoring using MLs. The wetness on one radio unit might be different from that on a different unit due to differing atmospheric conditions, antenna elevations, etc. As a result, this phenomenon might cause different attenuation levels from link to link, and add to the uncertainty in the measurements. On the other hand, a positive contribution of this effect is that it may be utilized as an additional fog detection parameter.

In order to reduce the measurement errors resulting from these different factors, the availability of multiple measurement sources was utilized, and the diversity of such sources, based on the availability inherent in the nature of typical microwave communication systems. Particularly, it enabled deriving an estimate for the wet antenna attenuation, and reduced the sources of random error. More research is needed regarding these issues in future work.

The spatial variability of the fog over the observed area is a central factor that may lead to disparities between all the different fog observation means. Previous studies showed that the fog may be of high variability in space e.g. with regards to its droplet size distribution (Gultepe et al., 2007). Temporal variations in the fog LWC as well as high differences between ground level concentrations to those measured several tens of meters off the surface in the same observed site have also been observed (e.g. Kunkel, 1984; Fuzzi et al., 1992).

During this study a system that provided one measurement every 24 hour period was used. The measurements were collected from several tens of links in a bounded area
of several square kilometers. This way of deriving the observations, may reduce the spatial resolution in the specific closed area. However, on the other hand, the representativeness of the microwave measurements, representing areal averages, is greater, particularly when compared to those measured by instruments, which are located at a single point, and are especially problematic from this point of view (Gultepe et al., 2007). One should note that, commercial systems with higher temporal resolution measurement exist e.g. systems that provide measurements every minute, or every 15 minutes (e.g. Goldshtein et al., 2009; David et al., 2013b). Additionally, MLs also operate at higher frequencies, e.g. around 80 GHz (Bridgewave AR80X). It is therefore expected that using higher resolution measurement systems to observe the phenomenon will improve the measurements and the ability to track lighter fogs.

Since LWC is highly correlated to visibility, several empirical models were developed to estimate one quantity given the other (e.g. Tomasi and Tampieri, 1976; Pinnick et al., 1978; Kunkel, 1984; Klemm et al., 2005; Acker et al., 2010). Of these, the model developed by Kunkel (1984) is commonly used for visibility estimations in many prediction models (e.g. Benjamin et al., 2004; Terradellas and Bergot, 2007). However, environmental conditions and the microphysical structure of fog also affect the visibility. Previous studies have shown that for a certain, constant, LWC level, visibility can vary (e.g. Klemm et al., 2005). Specifically, other research has indicated the dependence of visibility on $N_D$. For example, Meyer et al. (1980), show that visibility is a function of $N_D$ and varies with fog intensity. Thus, taking $N_D$ into account will allow visibility estimations with higher precision to be obtained. The warm-fog visibility parameterization developed by Gultepe et al. (2006) includes this parameter in addition to the LWC. The uncertainty estimation of this parameterization was found to be about 29%. While this uncertainty shows there is still room for improvement, it is nonetheless more accurate than the Kunkel (1984) model, which, depending on environmental conditions, over/under-estimated visibility by more than 50% (Gultepe et al., 2006). In the current work, $N_D$ was estimated from temperature measurements (Eq. (38)) which may introduce additional disparities (Gultepe et al., 2006). Notably, this formula was derived based on measurements which were taken within three types of cloud systems over Canada (Gultepe and Issac, 2004) while in this work it was applied for the first time in Israel (to the best of the author's knowledge), i.e. in different geo-meteorological conditions. A range of visibility was,
therefore, derived in order to obtain an order of magnitude when comparing to the visibility measurements taken by specialized instruments. Adding direct measurements of $N_D$ into the model will allow for improved estimation accuracy. Beyond the positive benefits of fog, this phenomenon poses a danger, particularly in cases of heavy fog that leads to disruptions and accidents in different transportation realms. MLs, which form the infrastructure of cellular communication networks, are widely deployed and exist in most places around the globe (Messer et al., 2006; Overeem et al., 2013). Use of the proposed method does not require additional expenses or installation of special equipment beyond standard meteorological measurements. On the other hand, application of the proposed technique can potentially contribute to the better understanding of fog related processes, as well as to the development of parameterizations for NWP models. Furthermore, the potential of the system for monitoring this phenomenon and providing real time warning of it is great.

4.2.2 Water Vapor

The results show good agreement between the conventional way to measure water vapor over the low troposphere and the proposed, novel method based on wireless communication networks measurements. Some disparities are, however, expected. That is since measurements from the microwave link are line integrated data, where in-situ measurements as made by a typical humidity gauge are point measurements. It was shown by Fabry (2006) that the spatial structure of moisture at surface level may be anisotropic. Thus, 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, one 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. Assuming this is being the case, the measurements of the central area humidity gauge do not correspond as well to the measurements of the microwave links that represent the average humidity along the paths (distances of some 4.5 km and 11 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., 2007b).

Beyond the feasibility shown in the work, much additional research is required in the future in order to understand and model the full set of factors interfering with humidity measurements, particularly in order to further investigate the potential applicability of the method.

The newly available data provided by the wireless communication facilities have the potential to provide moisture measurements and characterize its spatial and temporal variability. The wireless measurement technique can potentially be used in conjunction with conventional humidity gauges in order to obtain more accurate moisture fields.

Modeling water vapor and its dynamics is a fundamental aspect of meteorology. For example, it is used to support NWP models, and especially on a local scale. Current weather models have real limitations for predicting localized phenomena, such as thunderstorms, as these can be caused by the sudden development of clouds on a scale of just a few kilometers. A dense microwave network can potentially provide a continuous and reliable monitoring system for water vapor, and would be an important source of information for monitoring the behavior of water vapor before the formation of clouds. Additionally, its data could be integrated into NWP models, and could be used to establish early warning systems for flood events, that may have positive implications for disaster prevention and risk mitigation.
4.2.3 Rainfall monitoring in dry climate regions

Very little work has been carried out regarding precipitation measurements in dry climate regions. Here it was demonstrated that already-existing microwave networks deployed in such areas are able to provide vital, high resolution (spatial and temporal) information. The results above suggest that the method described here increases the probability of an early detection of single convective cells typical for these areas, and their associated precipitation, as compared to existing rain gauges. The results of the simulation that was carried out also support this conclusion. Specifically, in the rainfall event on 24 October 2008, the microwave links (located between Tzafit to Mirvat Mountain) detected precipitation 50 minutes prior to the first rain gauge indicating rainfall. In this case, the rain gauge found at Rotem plain area, entirely missed the precipitation. The second case-study, demonstrates the ability to provide precipitation data from a remote region where almost no other monitoring facilities exist, and again, at an earlier time with respect to the only two rain gauges; here, the links detected precipitation at about 1 hour and 40 minutes before the Mitzpe Ramon rain gauge and more than 2 hours before the one located in Ovda. The advantage of using the microwave system comparing to the radar may be considerable, when the radar rays are interrupted along the propagation path or when the convective cells are located too low in the troposphere, to be detected properly by the radar, as demonstrated in the 3rd case. This situation often occurs in dry climate areas which are located relatively far from the radar.

These results highlight the potential of commercial microwave links, particularly in connection to early detection and monitoring of damaging amounts of rainfall. Due to their climatic and hydrological conditions, dry environments are particularly prone to this dangerous phenomenon and from relatively small convective cells. The Judean and the Negev desert regions, which were dealt with here, are examples of such areas (see, e.g. Kahana et al., 2002; Cohen and Laronne, 2005; Dayan and Morin, 2006; Cohen et al., 2010; Shentsis et al., 2012). Intense rainfall is the main flash floods generating factor and hence the ability to predict this phenomenon highly depends on the availability of QPE taken directly from the flood area. With their combination of destructive power, incredible speed, and unpredictability, flash floods allow only few opportunities to provide timely warning. Thus, they rank among the most devastating weather related natural disasters. Rain gauge networks in these environments are
sparse while radar observations are often insufficient. In other cases, there may be no precipitation measurement equipment at all in these arid/semi-arid regions. Consequently, QPE information derived from existing microwave networks can provide the complimentary useful input required to successfully cope with this hazardous phenomenon.

4.2.4 Future work

Several studies have shown the ability of measuring precipitation using commercial microwave systems (e.g. Messer et al., 2006; Leijnse et al., 2007a, 2008; Zinevich et al., 2010; Chwala et al., 2012; Rayitsfeld et al., 2012; Wang et al., 2012), and the ability of creating two dimensional precipitation fields (e.g. Messer, 2007; Goldshtein et al., 2009; Zinevich et al., 2008, 2009; Overeem et al., 2013). As far as methodology, additional research is required to improve the performance of measurements using this approach. For example, the effect of wet antenna bias on the measured rain rates is a fundamental issue. It has been shown that the wet attenuation model is not invariant to spatial rainfall variability (Zinevich, 2010). If wet antenna correction coefficients are not taken into account, they may lead to considerable bias. While this aspect has received attention (e.g. Leijnse et al. 2008) it still requires more profound study. Additionally, the dependence of power law parameters on DSD may be inappropriate (Zinevich, 2010). Hence, future research could explore the possibility of retrieving DSD along the link path using attenuation data from orthogonal polarizations, and how the use of data from multiple channels may improve the accuracy of rain estimates (Wang et al., 2012). Further, estimation of absolute performance of the technique can only be achieved using large amounts of data (through rainfall distribution simulations and different microwave configurations) to gather reliable statistics. This can also be addressed in future research.

However, the goal of this work is not to present improvements in the rainfall monitoring technique, but rather, to show its potential for measurement, particularly in remote areas that are prone to flash flooding. In this sense, notably, that there are additional aspects that require further investigation in possible future research. Particularly, partial coverage of precipitation measurement instruments exists in many
areas, and these different measurement instruments (e.g. rain gauge, radar, microwave links) have different sampling and resolution characteristics. Goldshtein et al. (2009), for instance, presented a method to reconstruct rainfall intensity distribution using commercial microwave links. One of the advantages of the technique they describe is the possibility to easily integrate link measurements with rain gauge data and other sources allowing for improvement of estimation accuracy. An additional example of a method that would allow integration while providing the required synergy is use of Copula models (e.g. Vogl et al., 2012). A key future challenge in measuring precipitation using varied sources, that include microwave networks is, therefore, the ability to integrate the information received from the different tools in a way that recreates the precipitation field most precisely.

The current research focused on the Israeli regions of the Dead Sea, and the Negev, as examples of arid/semi-arid areas prone to flash flooding. However, precipitation detection, and estimation of precipitation intensity close to the ground, is a highly meaningful topic for this field on a global level. The threshold values for the initiation of flooding in flood prone regions, such as the Israeli Judean Desert, are often uncertain. These coefficients need to be extracted from the precipitation / run-off ratio. Due to a lack of precipitation data from these regions this problem often remains unsolved. In order to completely model the flood swell – the peak flow and the entire hydrograph (run-off volume and time span) – run-off coefficients such as the percentage of water created per square km from the entire precipitation during the storm are needed. These parameters are highly dependent on the intensity of precipitation, not only on its amount. Thus, wireless communications networks deployed in such areas can shed much light on the subject and provide vital information from which the required data can be derived. In order to test and quantify the suitability of this method for early warning in flood prone regions, hydrometeorological models for flood forecasting can be initialized using the QPE derived from the existing microwave systems, while observing a large number of events. The greatest contribution may be in developing nations, such as countries in Africa, where apart from flood inundation (Baldassarre et al., 2010) high percentage of the population rely on pluvial agriculture. However, currently, only few or no dedicated monitoring instruments are found in these countries (e.g. Mul, 2009) while,
on the other hand, commercial microwave infrastructure already exists in these countries (Overeem et al., 2013; Doumounia et al., 2013).

The current research has shown the potential for monitoring fog and humidity, and is, to the best of the author’s knowledge, the first in this field to discuss monitoring of these phenomena using existing commercial microwave links. Transforming these concepts into a practical application requires extensive experimental and modeling research. First, additional cases in Israel, and outside of it, in different climate conditions, need to be analyzed. Specifically, the two cases of fog discussed are extreme in their intensity and size (tens of kilometers spatially and very low visibility, dropping to a few tens of meters). As a result, collecting statistics for additional cases including lighter ones (that can be physically sensed by the system), is an important condition for understanding the practical capacity for observations. During this research meteorological reference data were taken from official surface stations located in the vicinity of the MLs. Measurement precision, and particularly that of the LWC and humidity, should further be researched and estimated, while comparing to measurements from specialized reference instruments which will be located with as close proximity as is physically possible to the MLs, e.g. beneath the propagation channels. A link along a single physical path was used for humidity measurements in each of the cases analyzed. Using multiple links that intersect each other over a relatively compact area may improve measuring precision, and this can be tested in future research. The current research utilized side information to identify and separate the different phenomena, and specifically to find as precise a baseline as possible. One of the major challenges, then, is minimizing the dependence on prior meteorological side information and examination of the ability to derive the reference level without it.

Excess attenuation due to antenna wetting during rainfall has been studied (e.g. Leijnse 2007c; Zinevich et al. 2010). Until now, this effect has been considered as a negative perturbation, causing additional attenuations to the radio signals and thus interfering with the ability to conduct accurate measurements. However, in some cases, this perturbation contains vital information, particularly during times whenever condensation rate exceeds the one of evaporation and when a dew layer accumulate directly on the antenna surface or the external radome. This water film may lead to a measurable signal loss, as preliminary observed here by the multiple MLs during the
fog episodes. Thus, the ability to detect dew by using the MLs system is interesting in and of itself.

Hening and Stanton (1996) estimated experimentally the microwave attenuation caused by dew using a parabolic reflector antenna. The experiment was conducted when a dew layer was known to be present on the antenna reflector. Then, the water layer was wiped off the antenna at a certain known time. Consequently, the signal level e.g. at a 20 GHz channel gained 0.5 dB immediately after the dew layer was removed.

The subject of antenna wetness during periods of high RH, then, requires further investigation, primarily in order to improve the measurement capability of the different phenomena (humidity and fog in particular) and more specifically, in order to assess the ability to detect dew episodes.

Collecting and comparing measurement statistics from a large number of links on days where condensation exists, and days when it does not will allow for an improved understanding of the effect the phenomena has on the system, and more clarity regarding the ability to detect the phenomena.

The effect of elevation (ranging from several meters to several tens of meters) off the surface on wettings of the antennas should be studied. The experimental verification should also take into account inherent uncertainty of reference data, including technical limitations of dew meters (Moro et al. 2007), difference in wetting properties of materials, in particular: the microwave radomes are artificial materials with possible different thermal properties comparing to those of soil or vegetation pallets where dew is naturally created. Also, the difference of orientation of the wetting surfaces – vertical for MLs vs. horizontal for typical dew meters. A possible effect of size and shape of different antennas on wetting properties should also be studied. In particular, one should note that fog-induced attenuation is comprised from attenuation due to the atmospheric path and the antenna wetting while dew-induced attenuation is only due to antenna wetting. Thus, in order to test the ability to detect dew, the latter can therefore be distinguished from fog, if RSL drop in multiple links is independent on link length. This approach can be, however, complicated by local character and spatial variation of the fog that can lead to inconsistency in RSL.
measurements for different links. The aim of future research will be to prove the suggested mechanisms as well as to identify their performance limits.

Notably, these days, modern mobile radio networks have an increasing need for high data rates and wide bandwidth. But, in most current networks, capacity expansion through coding and higher bandwidth has been maximized, and no further increase can be achieved through these means. In order to overcome this, higher frequencies are being implemented as a solution for access network expansion (Csurgai-Horváth and Bito, 2010). Radio links in bands as high as e.g. 80 GHz are already being implemented to fulfill these increased requirements (Bridgewave AR80X).

Thus, additional research could focus on links in this particular frequency range, where sensitivity to fog is greater, allowing for the measurement of lighter fog banks.

Additionally, there are links that operate around the 60 GHz range, where an oxygen absorption band exists (Van Vleck, 1947b). The water vapor attenuation around this band is about two orders of magnitude lower comparing to that induced by O₂ molecules, a fact that may allow observations of the variations of this parameter as well.

In more advanced stages and assuming earlier stages succeeded, multiple links operating for water vapor monitoring, and particularly links with high resolution (in the frequency and time domains) for fog monitoring could allow an investigation of the possibility of creating two dimensional maps of these phenomena. Finally, it is particularly challenging to investigate the potential for improvement by initializing meteorological models using these data from commercial microwave systems.
APPENDIX A

TECHNICAL NOTE: NOVEL METHOD FOR WATER VAPOUR MONITORING USING WIRELESS COMMUNICATION NETWORKS MEASUREMENTS
Technical Note: Novel method for water vapour monitoring using wireless communication networks measurements

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Abstract. We propose a new technique that overcomes the obstacles of the existing methods for monitoring near-surface water vapour, by estimating humidity from data collected through existing wireless communication networks.

Weather conditions and atmospheric phenomena affect the electromagnetic channel, causing attenuations to the radio signals. Thus, wireless communication networks are in effect built-in environmental monitoring facilities. The wireless microwave links, used in these networks, are widely deployed by cellular providers for backhaul communication between base stations, a few tens of meters above ground level. As a result, if all available measurements are used, the proposed method can provide moisture observations with high spatial resolution and potentially high temporal resolution. Further, the implementation cost is minimal, since the data used are already collected and saved by the cellular operators. In addition – many of these links are installed in areas where access is difficult such as orographic terrain and complex topography. As such, our method enables measurements in places that have been hard to measure in the past, or have never been measured before. The technique is restricted to weather conditions which exclude rain, fog or clouds along the propagation path. Strong winds that may cause movement of the link transmitter or receiver (or both) may also interfere with the ability to conduct accurate measurements.

We present results from real-data measurements taken from two microwave links used in a backhaul cellular network that show convincing correlation to surface station humidity measurements. The measurements were taken daily in two sites, one in northern Israel (28 measurements), the other in central Israel (29 measurements). The correlation between the microwave link measurements and the humidity gauges were 0.9 and 0.82 for the north and central sites, respectively. The Root Mean Square Differences (RMSD) were 1.8 g/m³ and 3.4 g/m³ for the northern and central site measurements, respectively.

1 Introduction

Atmospheric humidity has a cardinal part in a variety of environmental processes (e.g. Allan et al., 1999) in many fields. As the most influential of greenhouse gases, it absorbs long-wave terrestrial radiation. The water vapour cycle of evaporation and recondensation is a major energy redistributing mechanism transferring heat energy from the Earth’s surface to the atmosphere. Meteorological decision-support for weather forecasting is based on atmospheric model results (e.g. Shay-El and Alpert, 1991), the accuracy of which is determined by the quality of its initial conditions or forcing data. Hence, humidity, in particular, is a crucial variable for the initialization of atmospheric models. One of the central conclusions of the Mesoscale Alpine Programme (MAP), aimed at improving prediction of the regional weather and particularly rainfall and flooding, was that accurate moisture fields for initialization are essential (Ducrocq et al., 2002).

Current methods for obtaining humidity measurements include predominantly: surface stations, radiosondes and satellite systems. Common humidity instruments, found in surface stations, suffer from low spatial resolution since they provide only very local point observations. Moisture, in particular, is a field having unusually high variability in the mesoscale as demonstrated, for instance, by structure.
functions (Lilly and Gal-Chen, 1983). Furthermore, over heterogeneous terrain and complex topography, the spread of gauges is even more restricted due to often poor accessibility and positioning difficulties. Satellites, although they cover large areas, are frequently not accurate enough at surface levels while it is the near-surface moisture level that is, in most cases, the crucial 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.

For model initialization, a point moisture measurement close to the surface (about 2 m, as in a standard meteorological station) is not satisfactory due to local surface perturbations. For meteorological modeling purposes, an area average representing the near-surface moisture at an altitude of a few tens of meters, over a box with the scale of the model’s grid, is required. This type of data cannot, with use of current measuring tools, be effectively collected. The method we present provides a unique way of obtaining it.

As weather conditions and atmospheric phenomena cause impairments on radio links, wireless communication networks provide built-in environmental monitoring tools, as was recently demonstrated for rainfall (Messer et al., 2006, 2007; Leijnse et al., 2007) and areal evaporation (Leijnse et al., 2007) observations. In this paper we introduce a new technique to measure atmospheric humidity using data collected by wireless systems. 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.

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 datum point per 24 h (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/m³, 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. Rain, fog 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).

Another point of interest is the signal delay (and its variations) of the communication links studied. Using this delay provides an advantage in that in practice it is not affected by fog, clouds or rain along the propagation path. This fact is used in the application of inferring the atmospheric water vapour content from the signals of the GPS satellites (Bevis et al., 1992). However, the data presently used do not provide time delay values.

2 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. 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 H₂O molecule, might be attenuated, specifically 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.

The specific attenuation γ [dB/km] due to dry air and water vapour, at centimeter wavelengths, is well studied and can be evaluated (Rec. ITU-R P.676-6, 2005; Liebe, 1985) using the following procedure:

\[ γ = A_w + A_o \quad [\text{dB/km}] \]  
\[ γ = \frac{4\pi f N''}{c} \quad [\text{m}^{-1}] = 0.1820 f N''[\text{dB/km}] \]  

Where:

\( A_w \): The specific attenuation due to water vapour [dB/km].
\( A_o \): The specific attenuation due to dry air [dB/km] (Assuming the air is moist, \( A_o \) is one order of magnitude lower
than \( A_w \) since at frequencies of \( \sim 22 \text{ GHz} \), the attenuation is caused predominantly by the water vapour.

\( f \): The link’s frequency \([\text{GHz}]\).

\( N'' = N''(p, T, \rho, f) \): The imaginary part of the complex refractivity, measured in \( N \)-units, a function of the pressure \( p \) [hPa], temperature \( T \) [\( \degree \text{C} \)], frequency \( f \) [GHz] and the water vapour density \( \rho \) [g/m\(^3\)].

While:

\[
N'' = \sum_i S_i F_i + N''_D
\]

\( S_i = S_i (p, T, \rho, f) \): The strength of the \( i \)-th line [KHz].

\( F_i = F_i (p, T, \rho, f) \): 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).

Given measurements of the Received Signal Level (RSL), \( \gamma \) can be derived based on the microwave link’s measurements.

The RSL value chosen as the point of reference, only needs to be set once for each link, by subtracting the attenuation created by a typical moist air in the area over several weeks from the median RSL measurement of these weeks.

Consequently, given the atmospheric temperature, pressure and the link’s frequency, the water vapour density \( \rho \) [g/m\(^3\)] is estimated numerically through Eq. (2), using the known relation between \( N'' \) and \( \rho \).

As meteorological surface stations normally do not provide the absolute moisture \( \rho \), it was derived using the following formulas (Rec. ITU-R P.676-6, 2005; Liebe, 1985; Bolton, 1980):

\[
es_s = 6.112 \exp \left( \frac{17.67T}{T + 243.5} \right)
\]

\[
e = \frac{T + 273.15}{216.7}
\]

\[
e = \frac{100\%}{\varepsilon_s} \Rightarrow \text{RH}
\]

\( es \) – The saturation water vapour pressure [hPa].

\( e \) – The water vapour partial pressure [hPa].

\( T \) - The temperature [\( \degree \text{C} \)].

\( \rho \) – The water vapour density [g/m\(^3\)].

Hence:

\[
\rho = 1324.45 \times \frac{\text{RH}}{100\%} \times \frac{\exp \left( \frac{17.67T}{T + 243.5} \right)}{T + 273.15}
\]

### 3 Statistical tests

We investigated the correlation between absolute humidity values calculated using the method described, and those which were measured using a regular humidity gauge. The correlation analysis was performed by the Pearson’s correlation test, while the level of significance was set to 0.05. P-values were also calculated (Neter et al., 1996).

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

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

\( \rho_{mi} \) – The \( i \)-th water vapour density measurement as measured using the microwave link [g/m\(^3\)].

\( \rho_{gi} \) – The \( i \)-th water vapour density measurement as measured using the humidity gauge [g/m\(^3\)].

\( N \) – The number of samples (28 samples were taken from the northern site and 29 from the central Israel site). 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

Moisture observations using microwave links were made in several different locations in Israel, and at several different times. The results presented here (Figs. 1 and 2) are for Haifa (northern Israel, link frequency 22.725 GHz) and Ramla (central Israel, 21.325 GHz), during November 2005 and April–May 2007, respectively.

Figure 2 presents results for inter-daily variations in the absolute moisture which were calculated using data obtained from the wireless communication network, as compared to in-situ measurements, over a month. The results show a persuasive match between the conventional technique and the novel method, the correlation coefficient between the time series in the two presented cases is 0.9 and 0.82, respectively. In both cases, the \( p \) value is less than 0.05. The RMSD were found to be 1.8 g/m\(^3\) for the northern site and 3.4 g/m\(^3\) for the central site measurements. The presented results (2 cases) are examples of other cases, all demonstrating relatively good agreements. 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 h 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.

The largest difference between the traditional and the novel measurement methods (Fig. 2b) 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 Above Sea Level (a.s.l.) 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/m³. Further investigation is needed concerning this point.

5 Uncertainties

The following uncertainties were calculated based on the model (Rec. ITU-R P.676-6, 2005; Liebe, 1985) used in this study. The dominant uncertainty affecting the absolute humidity calculation is that of the attenuation quantization error. Due to 0.1 dB quantization error per link, the uncertainty in evaluating attenuation, for a 3.86 km link, is ±0.026 dB/km. As a result we get that the error in calculating absolute humidity for this link is of the magnitude of ±1 g/m³. 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/m³. Dry air effect on attenuation is one order of magnitude lower than that of water vapour in this case. Quantitatively it is 0.1 dB/km for dry air and 0.19 dB/km for water vapour.
as a result of humidity (for a link operating near 22 GHz, temperature of 15°C, humidity of 7.5 g/m³ 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″, 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: 0.045 N-units. The uncertainty depends on the path length, it is: ±0.006 N-units and ±0.003 N-units for the 3.86 km and the 11.05 km links, respectively.

The uncertainties in measuring temperature and pressure are of the magnitude 0.1 degrees Celsius, and 1 mb, respectively. But changes of this magnitude in pressure or temperature do not create a significant change in the absolute humidity calculation based on this model.

The estimated uncertainty in measuring humidity with regular humidity gauges is about 0.2 to 0.5 g/m³ (depending on the relative humidity and the temperature), while the error in measuring relative humidity was taken to be 3%.

6 Conclusions

The calculated, theoretical uncertainty for the measurement of the Ramla (central Israel) link is smaller in relation to the calculated uncertainty for the Harduf (northern Israel) link. The measurements from the northern link, on the other hand, present a better correspondence with the humidity gauge readings, which seems to go against the expectations from the error calculations. While it will need to be further studied, we can suggest several reasons for the observed discrepancy:

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 Ramla link is located some 100 m a.s.l. its transmitter and receiver are only 18 and 27 m above the surface of a fairly flat plane. It is possible then, that the Ramla link is more prone to surface reflection and interference (Leijnse et al., 2007).

The representativeness of the spot humidity gauges is also an error factor. It is possible that the humidity gauge in the Harduf area better represents the average humidity in the area than the Ramla humidity gauge does. Thus, it is possible that, while the distance between the humidity gauge and microwave link in the Ramla area is smaller than the distance in the Harduf region, the measurements of the Ramla humidity gauge do not correspond as well to the measurements of the microwave link that represent the average humidity along the link (a distance of some 11 km). Furthermore, 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 (especially if an inversion layer is being crossed), introduces additional disparities between the microwave measurements and those made by the conventional humidity gauges.

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.

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References


APPENDIX B

THE POTENTIAL OF COMMERCIAL MICROWAVE NETWORKS TO MONITOR DENSE FOG- FEASIBILITY STUDY
The potential of commercial microwave networks to monitor dense fog-feasibility study

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[1] Here we show the potential for dense fog monitoring using existing measurements from wireless communication systems. Communication networks widely deploy commercial microwave links across the terrain at ground level. Operating at frequencies of tens of gigahertz, they are affected by fog and are, practically, an existing, sensor network, spatially distributed worldwide, which can provide crucial information about fog concentration and visibility. The goal of this paper is to show the feasibility for fog identification and intensity estimation. A method is proposed and is demonstrated by two cases of heavy fog that took place in Israel. During these events, fog covered wide areas (tens of kilometers) and caused severe decrease in visibility, dropping as low as several tens of meters. Liquid water content and visibility values were estimated using measurements from tens of microwave links deployed in the observed area for each event. Each of the links provided a single measurement which was taken simultaneously across all of the links in the system. The values were found to be in the range of 0.5–0.8 g/m², high concentration values that match the maximum value range observed in field measurements carried out for prior studies in different test areas in the world. The visibility ranges calculated, between 30 and 70 m, fit the visibility assessments from the specialized measuring equipment operating in the observed area at the same time. These results point to the strong potential of the proposed technique.


1. Introduction

[2] Fog is defined as water droplets suspended in the atmosphere, near the surface of earth that reduce visibility to less than 1 km [American Meteorological Society (AMS), 2013]. The impact of fog on human beings and on the environment is considerable. Fog harvesting, for instance, can produce fresh water for gardening, afforestation, and even potable water that may have a significant contribution particularly in water scarce regions [Oliver, 2004; Klemm et al., 2012]. Moreover, in forest ecosystems, fog takes a cardinal part in the water balance of these natural environments [Dawson, 1998; Wrzesinsky and Klemm, 2000]. Information concerning the Liquid Water Content (LWC) of fog makes it possible to define the concentration of air pollutants through analysis of fog droplet samples [Tago et al., 2006]. An important role fog plays in cleaning the atmosphere through the process of particle scavenging and then drop deposition has also been shown [Herckes et al., 2007]. On the other hand, smog (a portmanteau of smoke and fog) may harm human health, adversely affect plants and damage structures [e.g., Wichmann et al., 1989; Dam and Hoang, 2008]. However, the central negative effect attributed to fog is reduced visibility that can lead to heavy financial damages, grave accidents, and loss of life [Croft et al., 1995; Pagowski et al., 2004; Gultepe et al., 2009]. The total economic impact of the presence of fog on aviation, marine, and land transportation can reasonably be compared to the impact of tornadoes or, in some cases, even those of hurricanes [Gultepe et al., 2007]. Furthermore, it has been recently shown that while the number of road accidents due to rain has declined considerably, the totals in foggy conditions have not changed significantly [Pisano et al., 2008].

[3] Existing means of measuring fog provide reliable measurements in most cases, but are limited in the spatial range they can cover, in their availability, and by their high implementation costs. Predominant techniques for detection of fog and measuring visibility include trained human observers, transmissometers, satellites, and instruments that measure the scatter coefficient. A trained human observer assesses visibility by the appearance or occlusion of objects at known distances from the observer’s present location. However, this assessment is a subjective judgment by a particular observer, one observer’s estimation might disagree with another’s when assessing the same visibility conditions. One of the most common instruments for measuring the light extinction...
coefficient is the transmissometer [World Meteorological Organization (WMO), 2008]. Although this device is considered very accurate, its costs are extremely high. An additional technique includes instruments measuring the scatter coefficient of light [WMO, 2008]. However, this technique only allows for a small sample volume to be measured. As a result, the visibility representativeness obtained is poor. Satellites have the advantage of providing large spatial coverage. Nevertheless, in some cases, they struggle to supply fog detections at ground level. High or middle altitude clouds along the line of sight between the ground and the system may obscure ground level fog [e.g., Ellrod, 1995]. It is also difficult to differentiate, using this technique, whether the observation reflects actual fog, or low stratus clouds, found at higher levels off the surface. Some instruments were designed to provide measurements of the fog LWC. While all are spatially limited, commonly used tools include the Particle Volume Monitor, Forward Scattering Spectrometer Probe, and hot-wire probes [Gerber, 1984; Arends et al., 1992; Emert, 2001; Schwarzenboeck et al., 2009].

At frequencies of tens of gigahertz, various atmospheric hydrometeors such as precipitation, water vapor, sleet, mist, and fog affect microwave beams, causing perturbations to radio signals [Rec. ITU-R P.838-2, 2004; Rec. ITU-R P.676-6, 2005; Rec. ITU-R P.840-4, 2009]. Thus, wireless communication networks can be considered to be built in environmental monitoring facilities, as was first demonstrated for rainfall observations [Messer et al., 2006; Leijnse et al., 2007a]. In particular, wireless communication networks seem to have suitable properties and the potential to monitor fog with certain potential advantages over existing monitoring tools. Typically, the Microwave Links (MLs) utilized in these networks are installed at heights of a few tens of meters off the surface, they are widely spread across the terrain and provide continuous measurements at high temporal and spatial resolution. Finally, the implementation costs are minimal since the requested data are standard data collected and logged routinely by the communication providers. However, most of the work done in this field of research till today was focused on the ability to monitor rainfall [e.g., Ravitsfeld et al., 2011; Chwala et al., 2012; Wang et al., 2012]. The ability to reconstruct the rainfall intensity distribution using multiple MLs in a given area has also been described [e.g., Goldshtein et al., 2009; Zinevich et al., 2008, 2009]. Only a limited amount of research has investigated the potential for monitoring other-than-rain phenomena using measurements from MLs. These works include, for example, estimating the areal evaporation [Leijnse et al., 2007b] and measuring the atmospheric water vapor [David et al., 2009, 2011; Chwala et al., 2013].

In this paper, we present the potential for monitoring of dense fog based on existing Received Signal Level (RSL) measurements from commercial microwave communication networks.

2. Method: Fog Identification and Estimation Using Measurements From Multiple MLs

Fog is one of the several atmospheric phenomena that affect MLs, causing an additional signal loss to the microwave electromagnetic beams with respect to that created during nonfoggy periods [e.g., Liebe et al., 1989]. Figure 1 presents the theoretical expected attenuation per 1 and 5 km, respectively, created by fog [Rec. ITU-R P.840-4, 2009]...
as a function of typical commercial MLs frequencies. These backhaul systems commonly operate in the frequency range between 6 and 40 GHz with bands characterized at 6, 11, 18, 23, and 38 GHz [Wells, 2009; Frenzel, 2013]. The system described is more sensitive to the effects of fog at the relatively high frequencies. Accordingly, the RSL measurements used in the current work were taken from links operating around the frequency of 38 GHz. The LWC within fogs typically ranges between 0.01 and 0.4 gr/m³ [Gultepe et al., 2007]. The calculations presented in Figure 1 were made for different LWC values starting at 0.1 gr/m³ and at different temperatures (10 and 15°C). The maximum values of LWC were taken from field measurements (including 5 min average values) carried out in the conducting of recent comprehensive field campaigns in different places in the world, using specialized equipment [Klemm et al., 2005; Herckes et al., 2007; Gultepe et al., 2009; Niu et al., 2010]. The horizontal dashed line indicates typical measurement resolution of a commercial ML (links with a coarser measurement resolution exist, but will not be the focus of this paper). We note that for longer links (Figure 1b), the effective sensitivity per kilometer increases, and lighter fogs can potentially be detected.

[7] Two fundamental stages in fog monitoring using measurements from multiple MLs are distinguished here: identification of the fog phenomenon and the estimation of its degree using additional standard meteorological instruments (temperature, humidity, and rain gauges).

[8] As our primary aim is to prove the feasibility of our proposed methodology, the technique was restricted to situations where other hydrometeors (rainfall, sleet, and snow) were nonexistent along the propagation path and we centered our research on extreme fog events.

### 2.1. Fog Identification

[9] We take a set—\(L_1, \ldots, L_N\) of MLs spread across the observed region within the same fog patch. In a typical cellular backhaul network [e.g., Zinevich et al., 2008], microwave links at different lengths and direction exist at an area of a size similar to a dense fog field, e.g., of the order of several square kilometers [e.g., Pagowski et al., 2004]. The availability of diverse RSL measurements enables us to identify the fog-induced component with higher statistical precision.

[10] A simplified model describing the attenuation of the \(i\)th microwave signal, \(\gamma_i\), can be described as follows [Zinevich et al., 2010]:

\[
\gamma_i = [A_{fi} + A_{pi} + A_{wi} + A_{ad} + \text{Noise}]_{ipy} \quad \text{(dB)} \quad (1)
\]

[11] Where the index \(i\) signifies the attenuation as measured by the \(i\)th ML, let us denote the following:

- \(A_{fi}\) Fog-induced attenuation;
- \(A_{pi}\) Attenuation as a result of other-than-fog precipitation (rain, sleet, and snow);
- \(A_{wi}\) Wet antenna attenuation. Because of the high level of humidity during fog, a thin layer of water may accumulate on the outside covers of the microwave antenna and may create additional attenuation to the received signal, beyond that caused by the fog in the atmospheric path;
- \(A_{ad}\) Water vapor attenuation;
- \(\text{Noise}\) All other random signal perturbations, e.g., which created as a result of winds that may oscillate the antennas, variations of the atmospheric refractive index, or temperature variations which may affect the analog circuitry of the microwave units [Leijnse et al., 2007b; Zinevich et al., 2010];

\[
\text{[d]} \quad \text{Each of the attenuation measurements, } \gamma_i, \text{ is quantized according to the given magnitude resolution of each commercial ML;}
\]

[12] In this study, we assume that \(A_{pi} = 0\). This assumption is validated using nearby standard measurements of rain gauges and temperature meters.

[13] In order to estimate the amount of wet antenna attenuation, \(A_{wi}\), and if it did in fact occur, we make use of measurements over particularly short MLs (preferably of up to a few hundreds of meters long) that are located near longer links, since the effect of fog, even a heavy one, as well as of water vapor on the signal attenuation at such short ranges is much smaller comparing to the attenuation created in longer MLs of several kilometers in lengths [Rec. ITU-R P.676-6, 2005; Rec. ITU-R P.840-4, 2009]. This being the case, any additional attenuation, if detected, can be directly attributed to the layer of water on the antennas, its value measured, and that value can be used to adjust the measurements on the longer links.

[14] In order to identify the specific attenuation created as a result of the fog itself, we set a baseline, zero RSL value separately for each link. Since the density of water vapor in the atmosphere affects MLs [Rec. ITU-R P.676-6, 2005; David et al., 2009, 2011] and since humidity is particularly high during fog, the zero level can be chosen by selecting the median value from RSL measurements taken over a period of several hours, during which the relative humidity in the area, as measured by the meteorological stations at the site, is around 90%. Alternatively, since the humidity difference between the foggy day and the reference day is known, the median RSL from the days adjacent to the event can be chosen (e.g., in cases where measurement occurs once daily), and a humidity correction to the baseline is carried out using a known physical model [Rec. ITU-R P.676-6, 2005]. By this selection of the base line, the water vapor effect, \(A_{vi}\), is minimized and is assumed to be zero.

[15] Thus, fog is identified as being present when the measured RSL value crosses the predefined threshold during times of high relative humidity (of ~95% and more), while the additional attenuation is observed simultaneously by the numerous MLs spread across the area.

### 2.2. Fog Density Estimation

[16] After detection of the existence of fog, the average amount of LWC per unit of volume in the fog was calculated, from which a rough estimation of the range of visibility was acquired.

#### 2.2.1. Liquid Water Content Calculation

[17] At the end of stage 2.1, we are left with the following:

\[
\gamma_i = A_{fi} + A_{wi} + \text{Noise}_i \quad \text{(dB)} \quad (2)
\]

[18] We note that the effective noise component as defined here, \(\text{Noise}_i\), includes the contribution from system quantization error.
The relation between the fog-induced attenuation, $A_{fi}$, and the total water content per unit volume is given by Rec. ITU-R P.840-4 [2009]

$$A_{fi} = \Phi_i \cdot \text{LWC} \cdot L_i \quad \text{(dB)} \quad (3)$$

where $L_i$ (km) is link length, $\Phi_i$ is a frequency and temperature dependent coefficient (known parameters), and LWC is the liquid water content ($\text{g rm}^{-3}$). In this work, we assume that all links deployed across the same fog field observe at the same temperature and the same LWC.

Given $\gamma_i$ measurements from N links operating around the same frequency and over the same fog patch, the effective fog-induced attenuation, $\bar{\gamma}_i$, can be extracted from N equations as (4) by a least squares or other estimation method and provide better accuracy than in the case of measurement from a single link

$$\gamma_i = \bar{\gamma}_i \cdot L_i + \bar{\gamma}_w + \text{Noise}_i \quad \text{(dB)} \quad (4)$$

While

$$\bar{\gamma}_i = \bar{\Phi} \cdot \text{LWC} \quad \text{(dB/km)} \quad (5)$$

Consequently, the LWC within the fog field is derived through the known relation (5).

$A_{sw}$ is the estimated wet antenna component calculated from the intercept of the linear line with the $y$ axis.

A mathematical model [Rec. ITU-R P.840-4, 2009] based on Rayleigh approximation is used for the calculation of $\Phi$, for frequencies of up to 200 GHz (fog drops typically range in size from several microns to a few tens of microns [e.g., Herckes et al., 2007; Gultepe et al., 2009], i.e., small with respect to millimeter microwaves):

$$\Phi = 0.819 \cdot \left[ \varepsilon'(1 + \beta^2) \right]^{-1} \quad \text{(dB/km)/($\text{gr/m}^3$)} \quad (6)$$

With $f$ being the link frequency (GHz), while

$$\beta = (2 + \varepsilon')/\varepsilon'' \quad (7)$$

The complete expression of the complex dielectric permittivity of water $\varepsilon(f, T) = \varepsilon'(f, T) + i\varepsilon''(f, T)$, is detailed in literature [Rec. ITU-R P.840-4, 2009].

Visibility Estimation

Visibility is defined as the greatest distance in a given direction at which it is possible to see and identify a prominent black object against the sky at the horizon in the daylight, or the greatest distance it could be seen and recognized during night if the general illumination were raised to the level of normal daylight [WMO, 2008].

In order to estimate the visibility ($V$), we used the following warm-fog visibility parameterization [Gultepe et al., 2006] which takes into account the droplet number concentration, $N_D$, in addition to the LWC

$$V = 1.002 \cdot (\text{LWC} \times N_D)^{-0.6473} \quad \text{(km)} \quad (8)$$

The formula is suitable for warm fog ($T > 0^\circ\text{C}$) conditions. $N_D$ can be measured directly using specialized equipment.

This value can be estimated given the temperature, $T$, by using the following known relation [Gultepe and Isaac, 2004]:

$$N_D = -0.071 \cdot T^2 + 2.213 \cdot T + 141.56 \quad \text{(cm}^{-3}) \quad (9)$$

We acquire a rough range of $V$ based on maximum and minimum bounds derived from the uncertainty in estimating this parameter.

3. Uncertainty and Bounds on the Visibility Estimate

3.1. Water Vapor Effect

Spatiotemporal variations in water vapor concentration [e.g., Fabry, 2006] affect the chosen baseline for calculating the fog-induced attenuation for each one of the links. Figure 2 presents the theoretical expected attenuation per 1 km (Figure 2a) and 5 km (Figure 2b) created by different water vapor densities as a function of the typical commercial MLs frequencies. The calculation was made for a temperature of 15°C in the humidity range between 25% and 100% which matches a water vapor concentration of between 3 and 13 gr/m³, respectively, at sea level pressure [Rec. ITU-R P.676-6, 2005]. A noticeable absorption line can be seen around the 22.2 GHz range [Van Vleck, 1947]. We chose the 38 GHz band where the sensitivity to fog is the highest in the given range (Figure 1). This choice is also advantageous since it is diverted from the absorption line (22.2 GHz) where humidity-induced attenuation is dominant [David et al., 2009, 2011; Čhwala et al., 2013].

The effect of water vapor on the baseline RSL chosen can be estimated by the difference between the expected attenuation curve under fog conditions (the 100% curve) and the humidity state at the time the reference measurements were taken (the 75% curve, representing a typical value for the conditions that were measured). This difference, at 38 GHz, is in the range between 0.05 and 0.3 dB for links of 1 and 5 km lengths, respectively. These values are of a lower order of magnitude with respect to the expected attenuation from high concentration fog (Figure 1). Nevertheless, we made a water vapor correction to the chosen RSL value according to the difference in the curves calculated for each link, using side information from the humidity gauges.

3.2. Liquid Water Content

The dominant source of uncertainty in estimating the LWC is the uncertainty in estimating the effective fog-induced attenuation, $\bar{\gamma}_i$. In order to estimate the error in this value, we used the error estimation formula for a linear slope [Kenney and Keeping, 1962]

$$\Delta \bar{\gamma}_i = \sqrt{\sum_{i=1}^{n} (\gamma_i - \bar{\gamma}_i)^2 \cdot \left( (n - 2) \cdot \sum_{i=1}^{n} (L_i - \bar{L})^2 \right)^{-1} \quad \text{(dB/km)} \quad (10)$$

Where

- $n$ Number of samples;
- $\gamma_i$ The attenuation measured by the $i$th link;
- $\bar{\gamma}_i$ The attenuation estimated by the linear approximation for the $i$th link;
- $L_i$ Length of the $i$th link;
- $\bar{L}$ Average length of the links.
Based on equation (5), uncertainty in estimating attenuation leads to uncertainty in the LWC estimation [Ku, 1966] which is given by

$$\Delta \text{LWC} = \Delta a_f \cdot \Phi^{-1} \text{ (gr/m}^3\text{)}$$  (11)

In this study, the uncertainty caused due to temperature variations was neglected while deriving equation (11). The difference between the temperature measurements of the different gauges (with an instrument error of 0.1°C) in the observed area was between 1 and 2°C at the time of the microwave system measurement. This uncertainty creates LWC variations an order of magnitude less than the uncertainty created from the effective fog-induced attenuation using the model [Rec. ITU-R P.840-4, 2009].

### 3.3. Wet Antenna

The estimation of attenuation resulting from a possible wet antenna, $A_w$, was carried out by evaluating the $y$-intercept of the line (which represents a theoretical distance of 0 between the antennas). In order to estimate the error in this value, we used the calculation for constant term error in a linear approximation [Kenney and Keeping, 1962]:

$$\Delta A_w = \sqrt{\sum \frac{1}{i} (\tilde{y}_i - \tilde{y})^2 \sum \frac{1}{i} L_i^2 \left[ n(n - 2) \cdot \sum \frac{1}{i} (L_i - L)^2 \right]^{-1}} \text{ (dB)}$$  (12)

### 3.4. Visibility Estimate Bounds

Since LWC is highly correlated to visibility, several empirical models were developed to estimate one quantity given the other [e.g., Tomasi and Tampieri, 1976; Pinnick et al., 1978; Kunkel, 1984; Klemm et al., 2005; Acker et al., 2010]. Of these, the model developed by Kunkel [1984] is commonly used for visibility estimations in many prediction models [e.g., Benjamin et al., 2004; Terradellas and Bergot, 2007]. However, environmental conditions and the microphysical structure of fog also affect the visibility. Previous studies have shown that for a certain, constant, LWC level, visibility can vary [e.g., Klemm et al., 2005]. Specifically, other research has indicated the dependence of visibility on $N_D$. For example, Meyer et al. [1980] show that visibility is a function of $N_D$ and varies with fog intensity. Thus, taking $N_D$ into account will allow visibility estimations with higher precision to be obtained. The warm-fog visibility parameterization developed by Gultepe et al. [2006] includes this parameter in addition to the LWC (equation (8)).

We set an upper and lower rough bound for the visibility assessment based on the contribution from two factors—the LWC uncertainty derived directly from the link measurements and from an assumed uncertainty which was taken to be 30% for the warm-fog visibility parameterization. Prior research [Gultepe et al., 2006] has shown that the uncertainty estimation for equation (8) is about 29%, where the uncertainties in LWC and the parameter $N_D$ taken into account in creating this estimate were 15% and 30%, respectively, and under the assumption that in visibility, fractional uncertainty is the sum of the fractional uncertainties in LWC and the parameter $N_D$. While this uncertainty shows there is still room for improvement, it is nonetheless more accurate than the Kunkel [1984] model, which, depending on environmental conditions, overestimated/underestimated visibility by more than 50% [Gultepe et al., 2006]. The formula was derived based on LWC in the range between 0.005 and 0.5 gr/m$^3$ and for values of $N_D$ between 1 and about 400 (cm$^{-3}$). We note that the...
estimation of $N_D$ in this paper was derived from the temperature (equation (9)), which may create additional disparities in estimating this parameter [Gultepe and Isaac, 2004; Gultepe et al., 2006] due to dependency on other physical and dynamic factors (e.g., nucleation and turbulence, respectively). To reach the visibility range presented here, first, the maximum and minimum values of LWC observed by the links were calculated, according to the uncertainty values associated with calculating LWC from attenuation measurements (equation (11)). Then, the visibility range was calculated from these minimum and maximum LWC values using equation (8) and assuming a 30% uncertainty estimate related to this calculation [Gultepe et al., 2006]. Based on these assumptions, in this paper, we note that the estimated visibility range is a measure of an order of magnitude. Adding information about the microphysical structure of the fog based, for example, on side information taken by proprietary instruments (e.g., direct measurement of $N_D$) will reduce the uncertainty in the visibility estimate, which is a matter for future research.

4. Results

[41] We centered our research on two extreme fog events that took place in Israel. In both cases, visibility dropped to or below several tens of meters, and the events continued throughout the night and the following morning. The thick fog developed to a scale of a few tens of kilometers, covered the southern and central coastal plain and lowland regions of Israel as well as parts of the Sinai Peninsula in Egypt, as illustrated by the satellite images (Figure 3a and 6a). The images were produced using the Clouds-Aerosols-Precipitation Satellite Analysis Tool [Lensky and Rosenfeld, 2008] based on infrared measurements from a combination of three of the spinning enhanced visible and infrared imager channels (IR3.9, IR10.8, and IR12.0). The extremely low visibility conditions during these fog events led to disruption, cancellations, and delays in the flight schedule for Ben Gurion international airport.

[42] Our analysis focuses on the central western coastal region (Tel Aviv City—Ben Gurion airport area) where several means for measuring the phenomenon exist. The microwave data used were gathered from the tens of commercial MLs operating at around the 38 GHz frequency range in the area that are located in the vicinity of the specialized measuring equipment. The links are installed at elevations between 5 and 90 m above sea level (asl), on towers that range from 5 to 100 m above ground level (agl) and span in length from 100 m to ~3.5 km. Each one of the links provides one measurement per day at a 0.1 dB resolution. The measurements are taken instantaneously and simultaneously across all of the links in the system at a prescribed time as reported by the cellular providers. During both events, no rainfall, sleet, or snow were measured in the examined area according to the observations of the surface stations.

4.1. Case 1: 9–10 December 2005

[43] Between the late evening of 9 December 2005 and the morning hours of the next day, a heavy fog front passing through central Israel was recorded by different observation techniques found in the area. At the surface, a ridge from the west with weak westerlies (and a long fetch over the Mediterranean Sea) was accompanied by a deep ridge aloft, which was causing significant subsidence.

[44] Since the microwave system that provided the data used for this research recorded measurements around 01:30, we used this time frame as the focal point for our research (all hours are in Universal Time Coordinated).

[45] Figure 3a shows the regional satellite image acquired during the event (01:27). Figure 3b indicates the location of the different measuring means in the region as well as the deployment of the ML system. According to the measurements...
of the three regional stations in the observed area (Figure 3b), the relative humidity (RH), as measured between 01:00 and 02:00, ranged between 97% and 100% (with temperature of around +13°C and wind speed of ~1–2.5 m/s).

Visibility assessments were acquired by two human observers located at the Beit Dagan station and at the Ben Gurion airport (Figure 4a). The Meteorological Optical Range (MOR) measurements [WMO, 2008] were taken by the three transmissometers located at the airport. According to these instruments, fog was detected starting from around 22:00 till 07:00 of the following morning.

4.1.1. Fog Identification and Intensity Estimation Using MLs Measurements

We used 88 MLs in the observed region during the event, deployed over 47 different paths, covering an area of approximately 5 by 6 km² (Figure 3b). Each of the links provided one measurement every 24 h (01:30). We compared attenuation measurements from the foggy night to those taken on a humid night without fog (according to the records from the different specialized measuring instruments).

4.1.1.1. Fog Identification

During the foggy night, on 10 December 2005, an RSL drop was recorded by numerous MLs, of different lengths, located in the area (during RH > 95% conditions). Figure 5a
presents the attenuation measurements from the different MLs, as a function of link length. Figure 5b shows the measurements which were acquired during a humid night (15 December) without fog (a RH of ~65%, ~90%, and 85% was measured by the Tel Aviv coast, central Tel Aviv, and Beit Dagan surface stations around 01:30). The additional attenuation measured by the links on the foggy night with respect to the humid night is apparent. During the foggy night, the Pearson correlation coefficient between observed attenuation to link length was found to be \( r = 0.55 \) (with \( P \) value < 0.01 [Neter et al., 1996] based on 88 data points).

Given the high RH of ~95% and the additional attenuation observed by the multiple MLs, fog was identified as being present in the area.

### 4.1.1.2. Estimating Liquid Water Content and Visibility

The estimate of the effective fog-induced attenuation, \( \dot{\alpha}_f \), is given by the slope of the resulting plot (Figure 5a). The estimate for the wet antenna component, \( \dot{\alpha}_w \), is given by the constant term.

A similar plot was created for the nonfoggy night, where the slope of the resulting graph tends to zero (Figure 5b). Given, \( \dot{\alpha}_f \), the temperature and the MLs frequency, we calculated the value for the LWC using equation (5). Then, minimum and maximum bounds on the range of visibility were derived using equations (8–11). The resulting values were \( 0.7 \pm 0.1 \) gr/m³ and 30 to 70 m, respectively.

### Table 1. Comparison of the Visibility Assessments and Microwave Measurements With the Specialized Measurement Instruments (10 December 2005)

<table>
<thead>
<tr>
<th>RH (%)</th>
<th>T (°C)</th>
<th>( \dot{\alpha}_w ) (dB)</th>
<th>LWC (gr/m³)</th>
<th>MLs Vis Max/Min</th>
<th>MOR (m)</th>
<th>B. Gurion Observer (m)</th>
<th>B. Dagan Observer (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>97–100</td>
<td>12–13.5</td>
<td>0.62 ± 0.15</td>
<td>0.63 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td>30–70 (01:30 h)</td>
<td>~50 (01:20–01:40 h)</td>
<td>100–400 (01:00–02:00 h)</td>
</tr>
</tbody>
</table>

The observations listed in the table were made over the same time when the ML measurements were taken, where the hour/time period indicated in parentheses in each column is the period during which the measurement was taken by each mean (the visibility range based on ML measurements indicates the upper and lower bound for the estimate). Temperature and RH measurements were acquired (at 10 min intervals) by the three ground stations between 01:20 and 01:40. The Ben Gurion and Beit Dagan observers provided visibility estimates once an hour and once every 3 h, respectively. The MOR measurements are based on 10 min intervals as acquired by each of the three transmissometers. The LWC, wet antenna, and fog-induced attenuation values measured by the MLs are also listed.

### 4.2. Case 2: 15–16 November 2010

Starting on the evening of 15 November 2010, a heavy fog front began developing and expanding along the area of Israel’s Mediterranean coast. At the surface, a Red Sea Trough with a central axis was moving eastward, allowing for northwesterly flow from the Mediterranean Sea to move into the coastal area. Aloft, a deep ridge was moving eastward. Fog conditions continued through the morning hours of 16 November 2010.

The satellite image shows the wide region affected during this fog event (Figure 6a), as well as the site discussed here, which is detailed in the map (Figure 6b) adjacent to the image.

![Figure 6](image_url)
The microwave system that provided the data used for this research recorded measurements at 22:00, and hence we used this time frame as the focal point for our research.

We focused on the area of Beit Dagan station (Figure 6b) in the proximity of MLs where the measured humidity was 90%–97% between 21:30 and 22:30 (with a temperature range of 18.5–19°C and wind speed of ~1 to ~3 m/s). Figure 7a shows the visibility results registered by the professional human observers located at Beit Dagan and Ben Gurion airport. The graphs described in Figure 7b are based on Runway Visual Range (RVR) measurements [AMS, 2013] of three transmissometers located at the airport. In addition, MOR measurements of a scatter meter found at Beit Dagan, which was available during this event, are also presented.

According to all of these observations, between 21:30 and 07:30 of 15–16 November 2010, severe visibility limitations were observed, decreasing to the order of a few tens of meters and less (between 22:00 and 01:00).

4.2.1. Fog Identification and Intensity Estimation Using MLs Measurements

58 MLs deployed in the observed region over 39 separate paths were used during the event (Figure 6b). The system is spread across an area of approximately 10 × 15 km² and captures one instantaneous measurement from each link every night (at 22:00). We compared the measurements taken on the foggy night to those taken during a humid night at the same hour.

4.2.1.1. Fog Identification

During the foggy night (15 November), an RSL drop was recorded by multiple MLs located in the area (at RH of ~95%). The attenuation measurements from the ML network in the area during this night are presented in Figure 8a. The correlation between observed attenuation and link length during the foggy night was $r = 0.57$ ($P$ value $< 0.01$, based on instant measurements at 5 min intervals.).
on 58 data points). Figure 8b shows the measurements taken on a humid night (10 November) without fog (RH ~87% around 22:00, according to Beit Dagan station).

[62] Given the high RH of ~95% and the additional attenuation observed by the multiple MLs fog was identified as being present in the area.

### 4.2.1.2. Estimating Liquid Water Content and Visibility

[63] The LWC value measured, using the same procedure described previously, was found to be 0.68 ± 0.15 g/m³. Accordingly, the range of visibility was assessed to be 30 to 70 m.

[64] Table 2 lists the ML measurements and the different visibility assessments as measured around 22:00 by the different measurement means.

### 5. Discussion

[65] The physical effects of fog on radiation in the microwave range are well studied [e.g., Liebe et al., 1989; Rec. ITU-R P.840-4, 2009; Csurgai-Horváth and Bitó, 2010]. The novelty of the work presented here is the concept of using existing commercial microwave infrastructure, as a fog detection tool, for measuring LWC and deriving visibility assessments. The challenges in fog monitoring using commercial MLs are mostly due to the fact that system measurements are optimized for communication quality of service, and not for meteorological observations, so factors such as link frequency, temporal resolution or quantization of the measurements are given. The opportunities come, on the other hand, from the availability of many links. These are widely spread across the terrain at relatively high densities and different lengths/heights, observing the atmospheric phenomenon simultaneously at various frequencies.

[66] Our results show that these systems have a potential for fog monitoring, especially in cases of heavy fog that creates severe visibility limitations particularly as it drops to the tens of meters range.

[67] The liquid water content values calculated from the microwave system measurements match similar high values measured directly in field studies, particularly when taking into account the error range in microwave measurements. Values above 0.5 g/m³ were observed in several recent studies during periods of dense fog [e.g., Klemm et al., 2005; Herckes et al., 2007; Gültepe et al., 2009; Niu et al., 2010].

[68] The visibility assessments calculated using the proposed method are of the same order of magnitude as the values measured directly by the different visibility measuring instruments and human observers during the same time period.

[69] Environmental and technical factors are both sources of error in estimating the fog-induced attenuation [Leijnse et al., 2007b; Zinevich et al., 2010]. Environmental factors include spatial variation of the fog, variation in the atmospheric refraction index, condensation of dew on the antenna radomes, and scatterers in proximity to the propagation path (e.g., fluttering tree leaves). Technical factors may be ascribed to e.g., system quantization and white noises, the effect of temperature changes on the analog circuits of the radio. All these directly affect the chosen reference baseline for a specific link. Another potential source of error is the possible wetting of the antenna during a fog event. The wet antenna effect is well known as a main source of error when measuring rainfall using a ML [e.g., Leijnse et al., 2008; Zinevich et al., 2010; Schleiss et al., 2013]. However, in our case, the source of possible wettings is different comparing to the case of rainfall since it is resulting from condensation of the atmospheric water vapor due to the high RH. Our results suggest that this effect is likely to be considerable also in the case of fog monitoring using MLs. We note that the wetness on one radio unit might be different from that on a different unit due to differing atmospheric conditions, antenna elevations, etc. As a result, this phenomenon might cause different attenuation levels from link to link and add to the uncertainty in the measurements. On the other hand, a positive contribution of this wet antenna component is that it may be utilized as an additional fog detection factor. In order to reduce the measurement errors resulting from these different factors, we utilized the availability of multiple measurement sources and the diversity of such sources based on the availability inherent in the nature of typical communication systems. Particularly, we were able to derive an estimate for the wet antenna attenuation and reduced the sources of random error. More research is needed regarding these issues in future work.

[70] During this study, we used a system that provided one measurement every 24 h period. The measurements were collected from several tens of links in a bounded area of several square kilometers. This way of deriving the observed value may reduce the spatial resolution in the specific closed area, but on the other hand, the representativeness of the measurement is greater, particularly when compared to those measured by specialized instruments, which are located at a single point and are especially problematic from this point of view [Gültepe et al., 2007]. One should note that commercial systems with higher temporal resolution measurement exist, e.g., systems that provide measurements every minute or every 15 min [e.g., Goldshein et al., 2009; David et al., 2013]. Additionally, MLs also operate at higher frequencies, e.g., around 60 or 80 GHz [e.g., Wells, 2009]. It is therefore expected that using higher resolution measurement systems to observe the phenomenon will improve the measurements and the ability to track lighter fogs.

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**Table 2. Comparison of the Visibility Assessments and Microwave Measurements With the Specialized Measurement Instruments (15 November 2010)**

<table>
<thead>
<tr>
<th>RH (%)</th>
<th>T (°C)</th>
<th>$\Delta_w$ (dB)</th>
<th>$\Delta_l$ (dB/km)</th>
<th>LWC (g/m³)</th>
<th>MLs Vis Max/Min Bounds (m)</th>
<th>MOR (m)</th>
<th>B. Gurion Observer (m)</th>
<th>B. Dagan Observer (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90–96</td>
<td>19</td>
<td>0.21 ± 0.15</td>
<td>0.68 ± 0.15</td>
<td>0.53 ± 0.1</td>
<td>30–70 (22:00)</td>
<td>30 to 950 Med = 70 (21:50–22:10 h)</td>
<td>50–500 (22:00–23:00 h)</td>
<td>Several meters–100 (22:00–23:00 h)</td>
</tr>
</tbody>
</table>

The observations listed in the table were made over the same time when ML measurements were taken, where the hour/time period indicated in parentheses in each column is the period during which the measurement was taken by each measuring mean. Temperature and RH measurements were acquired by the Beit Dagan ground station between 21:50 and 22:10 (at 10 min intervals). Observers provided visibility estimates once an hour. The MOR measurements were taken by the scattermeter at Beit Dagan in 1 min intervals. The notation “Med” indicates the median value.
Two fog events were investigated in the current study. Further research is required in order to assess the viability of the proposed method in the general case, beyond the events presented here. For example, a large number of events in different condition ranges and from different geographical regions need to be analyzed, as well as the need for, and dependence on, meteorological side information. Measurement precision, and particularly that of the LWC, should further be researched and estimated, while comparing to measurements from specialized reference instruments. Adding information about the microphysical characteristics of the fog in addition to LWC into the model will also allow for improvements in the visibility estimates [Meyer et al., 1980; Gultepe et al., 2006; Niu et al., 2010]. The aim of this study is to provide a proof of concept of the described system’s potential to monitor the phenomenon and these issues are left to future research.

Beyond the positive benefits of fog, this phenomenon poses a danger, particularly in cases of heavy fog that leads to disruptions and accidents in different transportation realms. MLs, which form the infrastructure of cellular communication networks, are widely deployed and exist in most places around the globe. Use of the proposed method does not require additional expenses or installation of special equipment beyond standard meteorological measurements. On the other hand, application of the proposed technique can contribute to the better understanding of fog related processes, as well as to the development of parameterizations for numerical weather prediction models. Furthermore, the potential of the system for monitoring the phenomenon and providing real time warning of it is great.

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APPENDIX C

THE POTENTIAL OF CELLULAR NETWORK INFRASTRUCTURES FOR SUDDEN RAINFALL MONITORING IN DRY CLIMATE REGIONS
The potential of cellular network infrastructures for sudden rainfall monitoring in dry climate regions

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Monitoring of precipitation and in particular sudden rain, in rural dry climate regions, is a subject of great significance in several weather related processes such as soil erosion, flash flooding, triggering epidemics and more. The rainfall monitoring facilities in these regions and as a result precipitation data are, however, commonly, severely lacking. As was recently shown, cellular networks infrastructures supply high resolution precipitation measurements at ground level while often being situated in dry areas, covering large parts of these climatic zones. The potential found in these systems to provide early monitoring and essential precipitation information, directly from arid regions, based on standard measurements of commercial microwave links, is exemplified here over the Negev and the Southern Judean desert, South Israel.

We present the results of two different rainfall events occurred in these regions. It is shown that the microwave system measured precipitation between at least 50 min (in case 1) and at least 1 h and 40 min (in case 2) before each of the sparse rain gauges. During each case, the radar system, located relatively far from the arid sites, provided measurements from heights of at least 1500 m and 2000 m above surface, respectively. A third case study demonstrates a relative advantage of microwave links to measure precipitation intensity with respect to the radar system, over an area of complex topography located in northeastern Israel, which is relatively far (~150 km) from the radar.

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1. Introduction

Dry climate, which can be further classified into arid and semi-arid climate types, cover more than a quarter of the world’s land area (Ahrens, 2003; Morin et al., 2009). However, precipitation data from these climatic environments, typified by severe water-scarcity, are severely lacking in comparison to more inhabited regions. Real time rainfall monitoring in such areas is of high importance from several different points of view. Although the total precipitation amounts in dry regions are low, the percentage of intensive rainfall events, generated by severe convection, is major. At the same time, in addition to precipitation, shallow soil with sparse vegetation, a quick decay of the infiltration curve, areas of bare rock, and large inclines of the ravines lead to high levels of peak flow and to the eruption of flash floods (e.g. Cohen et al., 2010; Greenbaum et al., 2006).

Moreover, as a result of the combination of these conditions, the soil erosion due to water is particularly high comparing to other climatic zones. Accelerated erosion by water (and wind) in dry regions is one of the causes of desertification and it exacerbates soil degradation (e.g. Lal, 2001). In addition, especially in warm semi arid and desert fringe regions, precipitation plays a significant role as a factor triggering epidemics (Grover-Kopec et al., 2005). Finally, it

Abbreviations: RSL, Received signal level; QPE, Quantitative precipitation estimates; DSD, Drop size distribution; IMS, Israel Meteorological Service; LT, Local time.

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has been shown that rainfall patterns have a strong impact on vegetation related processes as well as on the entire (arid and semi-arid) ecosystems (e.g. Lazaro et al., 2001; Rietkerk et al., 2002).

On the other hand, desert areas, such as those presented in this research, are particularly problematic for monitoring as the current measuring methods, if existing at all, provide only very limited precipitation data. State of the art rainfall observation systems include surface stations (rain gauges), weather radiosondes and remote sensing systems — radars and satellites. However, these techniques are expensive, not widespread and are often insufficient in their accuracy or in temporal/spatial resolution, especially close to the ground.

Conventional rain gauges, found at surface stations, provide an accurate measurement, but they measure locally, at a single point. In addition, the sparse deployment in dry areas cannot precisely represent precipitation change spatially in stormy rain events (e.g. Michaud and Sorooshian, 1994). Even if the number of gauges in a specific region was much higher, the ability to detect precipitation in a wide area based on this form of measurement would still be small. The probability that a single convective cell will miss the rain gauge entirely is high. Furthermore, even if precipitation was registered in one of the gauges, the likelihood of that particular gauge representing the maximum rainfall in the region is low.

Remote sensing systems provide a large amount of data over large spatial and temporal spans, and have greatly improved the ability to monitor precipitation in these areas. Of these remote sensing systems, the most common for precipitation measurements is the weather radar (Raghavan, 2003). These systems can provide precipitation data every 5 min with a spatial resolution of 1 km². The range covered by a typical radar system normally stands at around 30,000 km² (Morin et al., 2009).

Advanced weather radars can provide a wide range of detailed information about precipitation and the dynamics of rainstorms, from rainfall intensity and wind velocity, to the type and vertical structure of precipitation (Verlinde et al., 2002). Moreover, weather radars have shown to be useful in extending the predictability of flash floods (e.g. Morin et al., 2009). Despite this, radar data have had limited quantitative use in meteorological applications, because of errors and uncertainty in the surface precipitation estimates derived from it (Harrison et al., 2000). These errors and uncertainties are the outcomes of several factors, such as: calibration issues, the spatial expansion effect of the radar beam and problems with partial beam filling, problems with beam overshooting (Durden et al., 1998; Gabella et al., 2011) and high sensitivity of the rain rate–reflectivity relation to drop size distribution (DSD) variations (Jameson, 1991). In addition, dry desert areas are quite often not covered by radars.

It is obvious then, that the ideal measurement method would provide data from a wide spatial range, as the radar does, with close proximity to the ground, as is the case with rain gauges, directly from the areas of interest, at low costs. The advantage of the precipitation measurement method using the existing microwave networks is that it combines these exact characteristics. Cellular network infrastructure already covers large land areas all over the world, including regions that are difficult to access, such as complex topography, and particularly arid and semi-arid zones.

Weather conditions and rainfall in particular affect the electromagnetic radiation, causing attenuation of radio signals. Thus, microwave communication networks are in effect built in monitoring sensors of the environment (Messer et al., 2006). The skill of the method to measure precipitation (correlation with rain gauges), was found to be higher with respect to that of the radar system.

Microwave links are typically installed at elevations of only a few tens of meters above the ground level and as a result their measurements reflect the events close to the surface. In addition, many of these systems provide measurements at high spatial and temporal resolutions. Finally, since the data required by the method are only standard network data, the costs are minimal.

Rainfall monitoring, using microwave links, has been extensively studied over the past few years. These links have been shown to be useful for identifying dry and rainy periods (Chwala et al., 2012; Wang et al., 2012; Rayitsfeld et al., 2012) and for estimating path averaged rain rates (e.g. Leijnse et al., 2007a, 2008; Messer et al., 2006; Messer, 2007; Upton et al., 2005). Reconstruction of rainfall intensity distribution using commercial microwave networks has also been presented (Goldshtein et al., 2009; Zinevich et al., 2008, 2009). Other applications which were demonstrated include: areal evaporation measurements (Leijnse et al., 2007b), humidity monitoring (David et al., 2009, 2011), identification of melting snow (Upton et al., 2007), calibration and correction of radar systems (Krämer et al., 2005; Rahimi et al., 2006) and even monitoring of vegetation characteristics (Hunt et al., 2011). Here we demonstrate the ability to produce quantitative precipitation estimates (QPE) based on standard microwave network measurements taken directly from arid, rural regions and areas of complex terrain where radar and rain gauge techniques are often insufficient.

2. Method

The interpretation and modeling of atmosphere-induced impairments on radio links have been researched by telecommunication specialists for years. Several models, relating the attenuation rate $A$ (given in dB/km) with the rain intensity $R$ (mm/h), exist. One accepted approach is the power law model for the attenuation described as (Olsen et al., 1978):

$$A = aR^b$$

where the constants $a$ and $b$ are functions of frequency, polarization and DSD (Jameson, 1991). Given measurements of the received signal level (RSL), and transmission levels, parameters which are routinely collected by many cellular providers, the rainfall induced attenuation $A$ can be derived and hence the requested rain rate $R$ (Messer et al., 2006). In order to determine the base line level of the microwave measurements the median no-rainfall RSL measurements were chosen separately for each link over a no rain period (of at least 2 h) prior to the onset of the event. Then, these measurements were subtracted from those acquired during the rainfall event itself. Finally, wet antenna attenuation correction was applied (Zinevich et al., 2009).
3. Sources of error

Both environmental and instrumental effects are sources of error in estimating path-averaged rainfall for a link. A major source is the baseline uncertainty. Fluctuations of atmospheric humidity are a primary cause of baseline level variations over time, as well as ducting and scintillation effects. Temperature variations affect the analog circuitry of the transmit and receive units which may lead to additional signal variations. In addition, mechanical oscillations, such as those caused by winds moving the microwave antennas or alternately scatterers found close to the propagation path (e.g. moving tree leaves) may also cause variations in the baseline signal (Leijnse et al., 2007b). Baseline uncertainty dominates system quantization error uncertainties, as well as errors resulting from DSD variability along the link. Additional sources include wet antenna effects and spatial variability of rainfall in the vicinity of the link, which affects the accuracy of QPE out of the link path. Extensive research analyzing and quantifying the various sources of perturbations has recently been conducted (Zinevich et al., 2010).

4. The Dead Sea and north Negev regions

The Negev desert, which constitutes the southern half of Israel, is an arid climate region extending between the latitudes of 29° North and 31°20 North (Kidron, 2000; Jacobs et al., 2002; Kahana et al., 2002). The climate found in the area of the Dead Sea (which borders with the northeast part of the Negev) spans from arid in the south part and near its shores, to Mediterranean, semi arid climate, in the north (Cohen and Laronne, 2005; Dayan and Morin, 2006).

Severe convection generates heavy precipitation in these regions while two dominant synoptic systems account for most of the major rainfall events (Dayan and Morin, 2006; Kahana et al., 2002; Krichak et al., 2000). One of these is the Red Sea trough—a tropical synoptic scale system. This barometric trough is accompanied by an upper-level trough which develops over Egypt, providing favorable conditions for the development of severe convective storms. Alpert et al. (2004) have shown that the frequency of Red Sea troughs was doubled over the last 5 decades. The second synoptic system contributing to rainfall in the area is a Syrian Low—an intense Mediterranean cyclone which is centered over Syria.

In the cases demonstrated below it is shown that the radar system covers the middle of the country, while the arid climate study areas, are in the south. As a result, due to the curvature of the Earth and the radar beam transmission angle, the radar precipitation measurements over these areas are distant from the surface at an elevation of about 2000 m above ground level in the case of the north Negev region. In the southern Dead Sea area, in addition to the aforementioned problem, the radar beam, and particularly the one that is transmitted at the lowest elevation angle (which is targeted at providing precipitation measurements from elevations closer to the ground) is disrupted by the regional topography. The data, from the minimal elevation, acquired in this case, are actually measured at an altitude of about 1500 m above the ground. Therefore, precision of these QPE is doubtful.

5. Results

Three case-studies are presented. The first two are the two rainfall events that occurred in the arid region of the southern Judean desert and in the northern part of the Negev. The 3rd case-study is based on a rainfall event occurred in northern Israel over an area of complex topography. The microwave system, spread across the tested regions, provides minimal and maximal measurements per 15 minute intervals for each link. Accordingly, the maximal and minimal rainfall intensities were derived based on these measurements (Messer et al., 2006). The microwave link values represent the average measurement of several links that are routed over the same physical path. The attenuation measurements of the links were related to rainfall only when attenuation was simultaneously recorded on several links over the same propagation path. Three radar images are presented (Figs. 1A, 2, and 5A) while the convective cells in each image are overlaid on a physical map of the region. The color of each cell indicates the QPE according to the scale found to the right of each image.


There are 32 relatively long microwave links deployed in the first examined region of the southern Judean desert (Fig. 1A). The system’s frequency range is 17–19 GHz with a quantization error of 0.1 dB. These links span from 6 to 26 km in length, across an area of approximately $60 \times 30 \text{ km}^2$. All links are installed between 10 and 50 m above ground level and are spread across seven different physical paths (transmitting more than one link over the same physical path is possible by varying link frequency and polarization). The results presented for this case study are derived from 29 of the 32 microwave links found in the region (in some cases, some links were not employed due to a technical malfunction or lack of data for the particular link). Also presented are measurements from 6 Israel Meteorological Service (IMS) rain gauges located at the examined area. On the night between 24 and 25 October 2008, heavy precipitation fell in the Judean desert and the Negev over short periods of time. Cold air at high altitude and the entrance of humidity from Jordan in the east, created a well developed convective cloud, covering the northeastern Negev, and southern Judean desert (Fig. 1A).

The IMS rain gauges which are deployed in the area, as well as the network of microwave links are depicted in Fig. 1A. A convective cell (green) can be seen in the Tamar Fort region. The rainfall in this area was detected by the microwave links in the vicinity (at least 50 min) long before the rain gauges in the area as can be seen in Fig. 1B–E. The cell did not pass over all the specific point-locations of the rain gauges in the region.

Among the rain gauges, the Sdom gauge was the first to measure precipitation only at 21:50 local time (LT). The Rotem plain rain gauge did not indicate precipitation at all while many of the microwave links located at the area indicated precipitation.

As can be seen from the microwave link measurements (Fig. 1B–C) the cloud movement, in this case, was from south to north. As a result the relatively southern links were the
first to measure precipitation as early as 21:00 LT. Finally, the northernmost links, of Beit Yatir–Shima and Beit Yatir–Arad physical paths, detected precipitation.

A simulation was carried out in order to evaluate the effectiveness of the microwave links in capturing the precipitation in comparison to the rain gauges across the study region.

Fig. 1. The microwave links and rain gauges located in the arid region are superimposed over a magnified radar image (A) which was acquired at 21:00 LT. The color of each convective cell indicates the rainfall intensity according to the scale found to the right of the image. B–E: Maximal (B) and minimal (C) intensities of precipitation as measured by the microwave links, compared to that measured by the IMS' rain gauges (D and E) located in the area. The Rotem plain rain gauge, not depicted here, did not measure precipitation at all. The indicated time represents the first detection of precipitation.
The locations of the precipitation stations and microwave links in the area were mapped. Random circles of a 5 km radius were inserted into the simulation area to represent the convective cells in the region. In the simulation the cases where the location of a convective cell corresponded with a microwave link below it, were counted. Where several links corresponded with a single convective cell, the occurrence was counted only once.

Similarly, all cases where a convective cell was located above the rain gauges, were enumerated. The simulation was run for 10,000 cases in which 10,000 convective cells were randomly positioned above the simulation area. The results showed that the probability of detecting a convective cell with the microwave links located in this region was 3.6 times greater than the probability of detecting one using a rain gauge (26.6% against 7.3%, respectively).

5.2. Case 2: 17–18 January 2010

On January 17–18, 2010, the Negev, Arava (and Sinai) regions experienced relatively high levels of precipitation. Several IMS rain gauges deployed in the region measured rainfall levels of 30–80 mm that, in some cases, equaled the entire yearly average for the region. This event was generated due to a cold air surge in the middle atmospheric layer in conjunction with an equatorial moisture layer below which was advected to the region from central Africa by the sub-tropic jet stream (Ziv, 2001).

Fig. 2 presents the radar image acquired at 19:00 LT on January 17.

Fig. 3 details the study area including the locations of the microwave links deployed at the site along with two online meteorological service rain gauges at this location. In this case, we used the measurements of 4 microwave links located over 2 different physical paths. The lengths of the links range between 9.5 and 13.2 km, and they operate in the 18–23 GHz frequency range with a quantization error of 0.1 dB. Links are installed between 27 and 70 m above ground level.

Fig. 4, shows the rain rates as deduced from the microwave links (maximum and minimum) along with the rain gauge measurements.

As early as 16:30 LT, the two links located between Nafha and Mitzpe Ramon (Fig. 3) already started indicating rainfall (of low intensity though). Larger amounts of precipitation can be seen from 18:15, further increasing at 18:15–18:30. Beginning at 18:30, rain is also measured simultaneously on the Nafha–Lavan mountain links, indicating that, during this

Fig. 2. The IMS radar image which was taken at 19:00 LT on January 17. The study area is marked by a circle. The radar measurements from this region are taken at an altitude of about 2 km above the ground.
time slot, rainfall fell over the specific area of the farm located by the links’ intersection point. On the other hand, the Mit"{o}pe Ramon rain gauge started measuring precipitation at 18:10 till 18:30 and again at later times while the Ovda gauge started measuring only at 18:40. Other rain gauges, installed at more remote locations (at distances of about 25 to 50 km) from the test site, have started measuring rainfall also only from 18:40 LT or at later times.

5.3. Case 3: microwave links vs. radar measurements from a relatively remote area of complex terrain

An advantage of the microwave links over the radar system is demonstrated, based on measurements taken during a rainfall event which took place on 11 December 2010 at the Golan Heights, a volcanic plateau spread over an area of 1040 km² (Yom Tov et al., 1995) located in the eastern side of the north Jordan valley (northeastern Israel, as seen in Fig. 5A), about 150 km away from the radar’s location in central Israel. The topographic heights, in this region, range from ~2200 m in the north to below sea level in the south. In this case, the radar beam that is transmitted at the lowest angle reaches an elevation of about 2000 m above sea level in this location. In addition, during this event, the radar rays were propagating through many Cumulonimbus clouds which were found along the propagation path, across a distance of a few tens of km (Fig. 5A). As a result of these conditions, the radar system underestimated the actual rain rate over the region. Two microwave links transmitting on the same physical path are located in the area. A rain gauge is located 6.5 km from the northern end of the links (Fig. 5B). We compared the rain rate measurements from the microwave system to the radar measurements under the assumption that the rain gauge describes the ground truth. Each of these methods provides measurements in different ways: The microwave links provide maximum and minimum rain rate measurements every quarter hour. Radar provides measurements of rain rate every 5 min, and the rain gauge measures the amount of rain accumulated in every 10 minute period. Therefore, to allow for a comparison to be made, we chose a common base for the three tools as far as the measured time interval, as well as the measured quantity (rain rate). Since the links provide a maximum and minimum measurement every 15 min, one can deduce that precipitation was continuous in intervals where the minimum and maximum measurements are both greater than zero. During intervals where only a maximum value was observed — one can deduce that the precipitation occurred for a period of less than 15 min. To correlate the rain gauge and microwave measurements, we used the maximum measurements of the links that include measurements of precipitation intervals shorter than 15 min. We correlated the measurements over a half hour interval, from which the maximum rain gauge and link measurements, respectively, were chosen. The correlation coefficient derived from a Pearson correlation test (Neter et al., 1996), was 0.85 (based on measurements taken between 04:30 and 18:30 LT). We correlated the radar QPE from the area to the rain gauge measurements, using the same time interval (half hour) and for the same time period (04:30 to 18:30 LT). The maximum reading from the rain gauge every half hour was compared to the maximum radar measurement during that same half hour. The correlation coefficient was 0.2. We then compared the intensity measurements. Fig. 5A shows a radar image taken during the storm event at 13:00 LT. Fig. 6 presents the rain rate measured during the entire event, by each of the methods, in the observed area. The rain gauge measurements can be seen to fall between the minimum and maximum QPE of the links. On the other hand, the radar measurements underestimated the intensity compared to the rain gauge and observed precipitation rates of ~1 mm/h during the whole storm event.

These results show the great potential of microwave systems to provide reliable rain rate measurements with high resolution from areas where, at times, the radar system does not provide sufficient response.

The disparities between the link measurements to those of the rain gauge are expected, primarily due to spatial variability of the rainfall (Zinevich et al., 2010). Additionally, the links provided measurements of the minimal and maximal intensities which were taken instantly while the gauge’s intensity rates were derived based on the amount of liquid water that has accumulated inside the instrument during a 10 minute time interval.

Fig. 3. The microwave links in the site at the northern Negev. The physical paths of the 4 links are marked as lines while the two meteorological service rain gauges, are denoted by triangles. As a result of the strong rainfall, most of a farm located in the area, was severely damaged. Of some 80,000 m² of vineyards, only 9000 m² remained — the damaged centers are indicated by asterisks.
6. Summary

Very little work has been carried out regarding precipitation measurements in dry climate regions. Here we have demonstrated that already-existing microwave networks deployed in such areas are able to provide vital, high resolution (spatial and temporal) information. A key challenge in measuring precipitation using varied sources (e.g. rain...
gauge, radar, microwave links) is the ability to integrate the information received from the different tools in a way that most precisely recreates the precipitation field. Particularly, when each measuring instrument has different sampling and resolution characteristics. Goldshtein et al. (2009), for instance, presented a method to reconstruct rainfall intensity distribution using commercial microwave links. One of the advantages of the technique they describe is the possibility to easily integrate link measurements with rain gauge data and other sources allowing for improvement of estimation accuracy. An additional example of a method that would allow integration while providing the required synergy is the use of Copula models (e.g. Vogl et al., 2012).

The results above suggest that the method described here increases the probability of an early detection of single convective cells typical for these areas, and their associated precipitation, as compared to existing rain gauges. The results of the simulation that was carried out also support this conclusion. Specifically, in the rainfall event on 24 October 2008 (case 1), the microwave links (located between Tzafit to Mirvat Mountain) detected precipitation 50 min prior to the first rain gauge indicating rainfall. In this case, the rain gauge found at Rotem plain area, entirely missed the precipitation. The second case-study, demonstrates the ability to provide precipitation data from a remote region where almost no other monitoring facilities exist, and again, at an earlier time with respect to the only two rain gauges; here, the links detected precipitation at about 1 h and 40 min before the Mitzpe Ramon rain gauge and more than 2 h before the one located in Ovda. The advantage of using the microwave system comparing to the radar may be considerable, when the radar rays are interrupted along the propagation path or when the convective cells are located too low in the troposphere, to be detected properly by the radar, as demonstrated in the 3rd case. This situation often occurs in dry climate areas which are located relatively far from the radar.

These results highlight the potential of commercial microwave links, particularly in connection to early detection and monitoring of damaging amounts of rainfall. Due to their climatic and hydrological conditions, dry environments are particularly prone to this dangerous phenomenon and from relatively small convective cells. The Judean and the Negev desert regions, which were dealt with here, are examples of such areas (see, e.g. Cohen and Laronne, 2005; Cohen et al., 2010; Dayan and Morin, 2006; Kahana et al., 2002; Shentsis et al., 2012). Intense rainfall is the main flash flood generating factor and hence the ability to predict this phenomenon highly depends on the availability of QPE taken directly from the flood area. With their combination of destructive power, incredible speed, and unpredictability, flash floods allow only few opportunities to provide timely warning. Thus, they rank among the most devastating weather related natural disasters. Rain gauge networks in these environments are sparse while radar observations are often insufficient. In other cases, there may be no precipitation measurement equipment at all in these arid/semi-arid regions. Consequently, QPE information derived from existing microwave networks can provide the complementary useful input required to successfully cope with this potentially hazardous phenomenon.

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לשעה וארבעים דקות (אירוע מספר 2) הלני כל חודשزاد מנשי המוצעי הוזניים המזעריים באזור.

במהלך כל אירונ, מעריצת המכוון"ם הממוכמת של רוח מהאיון הארדיים, סיפקה ממדית מנביה של לעות 1500 מטר ו-2000 מטר לעיל ההשיט מואז מזר הגשם, בצאתה, ממדית אשר עשויה של גליצי שנה את הגשם בראש מפל הקרקע. ממדת שליש, ממדית את הייתון הגשם של מרוכבת מחלקה מחיית קימון, לממדד עוצמתי ושם ביצת מפורכים למעיון"ם באזורי רמת הגולן, שבירשלן, המרבות באז מזרחי (ב 150 ק"מ).

התוצאות בעובד מזובשות על הפרטוניאל החזק של השיטה המוצעת לשפおすすめ את האנימורהית המכאורה ניקית. הפיכת הגישה הקונספואלה לשימוץ בפגוע דרשב המשך בהנה.

ומחק עתידי גוסף.
The study presented in this work is divided into three parts, each focusing on a different atmospheric phenomenon.

The first part of the work aims to demonstrate the feasibility of detecting and estimating the intensity of fog. The method proposed is illustrated with two severe fog cases that occurred in Israel. During these events, fog covered large areas (up to tens of kilometers) and caused severe visibility restrictions, reaching only a few meters in altitude.

The values calculated were found to be within the range of 1.0 to 1.0, indicating high concentrations similar to the maximum values recorded in specialized equipment used in field surveys in other parts of the world. Estimated visibility ranges, between 31 and 01 meters, also correspond to the estimates obtained by specialized equipment that operated in the area during these events.

Another part of the work demonstrates the potential of these systems to provide measurements of atmospheric water vapor concentration. The work presents measurements based on commercial microwave systems and finds good correlation with ground-based meteorological station measurements. Measurements were taken on a daily basis from two sites, one in northern Israel and the other in the center. The correlation between microwave measurements and dedicated radar measurements ranged from 1.02 to 1.0 for the two sites during the highlighted events.

Detection of rainfall in arid climates is a crucial subject in many natural processes, especially in relation to flash floods, erosion (erosion), volcanic eruptions, and others. However, due to the lack of an effective monitoring system for rainfall in these areas, the information about the phenomenon in these regions is extremely limited.

On the other hand, these systems are often installed in these areas and cover vast areas. The aim of this part of the research is to demonstrate the potential of these systems already in place in these challenging areas to provide early and necessary rainfall monitoring directly from the site based on standardized data from commercial microwave systems. This potential is demonstrated in the Negev and Judea Desert, located in the south and southeast of Israel.

A scientific research conference was held in Fez肤l, the capital of Morocco, which is characterized by arid climate. The conference, titled 'Geological and Geophysical Research', is a platform for researchers from many countries to exchange their ideas and discuss their latest findings in these fields.
הפקולטה למדעי מדע קיים ע"י רים מרדכי וברלי סאקר
הוחתגלואפניקה והמדעיים אטמוספריים פלנטאריים

骛ור אדני מים, ערפל וגלם באמדאוות מידות
מערבות מייקרוגל מנזריות

חיבר Lawrence 허אר "פרופ" לתורה פילוסופית

משי ע"י

עבידתו ועשתה התדהמה של פרופ' פינחס אלפרט פרופ' חוג מפרקים

משי לסלומט של אוניברסיטת תל אביב

שבת תשמ"ע

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