Nanoscale interparticle distance within dimers in solution measured by light scattering

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Abstract — The design, realization, and measurement results of a high-accuracy multiyear 3.5 GHz trans-horizon radio propagation measurement system are discussed, with both emphasis on the results and implemented technical measures to enhance the accuracy and overall reliability of the measurements. The propagation measurements have been performed on two different paths of 253 and 234 km length, using two transmitters and one receiver in the period September 2013 till November 2016. One of the paths travels over wetland; the other path can be considered as a land path. On each path, an additional transmitter is placed at 107 km (in the 253 km path) and 84 km (in the 234 km path) from the receiver. With this arrangement, the correlation between two nonaligned paths of comparable length, and two aligned paths of dissimilar length, was studied. The measurements show that for the land path, the predicted ITU-R P.452-16 cumulative distribution function (CDF) typically shows 5 dB higher path loss than the actual measured CDF for the region of interest; anomalous propagation. This means that the measured signal is on average weaker than predicted (a higher path loss). For the wetland path, the actual CDF is very close to the predicted CDF. Also, the measurements reveal that typically 30% of the anomalous propagation occurrences are correlated with other paths.

Index Terms — Aircraft scatter, correlation, ducting, measurement accuracy, radio wave propagation, rain scatter, super high frequency (SHF), trans-horizon, troposphere.

I. INTRODUCTION

In spectrum management, statistical models for radio wave propagation are required to arrive at informed decisions on the compatibility of planned wireless applications. The higher the accuracy of these models, the lower is the probability of interference on the one hand, or the higher the efficient use of the spectrum on the other hand. For that reason, Study Group 3 of the Radio Sector of the International Telecommunication Union (ITU-R) has established propagation models for a large range of frequencies and applications [1]. The Radiocommunications Agency Netherlands (AT) is actively involved in this group. For instance, the organization provided empirical data of eight UHF trans-horizon mixed land-sea propagation paths [8], [9] to Study Group 3 in 2011. These models may be based on empirical data or theoretical formulations, or both. To verify these propagation models in a variety of terrains, propagation measurements are indispensable. In this paper, the ITU-R recommendation P.452 has been verified with measurements in The Netherlands. A nonexhaustive set of examples of such measurements is given in [2]–[7].

Typically, prediction models are generic and measurements usually specific for the local situation. The results in this paper can be used in similar European situations, but can also be used to refine prediction models. The Netherlands is very flat, but also wet: 60% of its surface is less than 10 m above mean sea level and 85% is less than 25 m above mean sea level. A large part of the country consists of the Rhine–Meuse–Scheldt river delta and is densely populated like other river deltas in the world. Therefore, propagation measurements in The Netherlands provide a unique and also important data set for the verification of propagation models for flat wetland terrains like river deltas.

The 3.5 GHz propagation measurements were motivated by introduction of broadband wireless access (BWA) devices to the 3.4–3.8 GHz frequency band in Europe, together with the necessity to protect existing earth-space downlinks for military intelligence applications in the Netherlands. The Dutch Ministry of Defense utilizes this frequency band for eavesdropping of satellite communication purposes (reception only) and hence require a very high availability; much higher than commercial applications. In Europe, but also other parts of the world, this 3.5 GHz band is on the other hand envisaged to be widely used for 5G mobile networks. For these reasons, it was decided to empirically verify the associated propagation model, ITU-R Recommendation P.452-16 [10] on trans-horizon paths in the flat terrain typical of The Netherlands. Similar measurements have been done previously by Inmarsat...
and Stratos in the Netherlands between 2008 and 2010. However, in this case, only a single path having a smaller distance (137 km) was covered.

The dominant source of anomalous propagation (ducting) is caused by specific weather conditions in the lowest several hundred meters above ground. Predicting such conditions is very important to minimize interference and malfunctioning of wireless systems on the same frequency. For instance, by reducing the transmit power in such situations. Especially in case of dynamic spectrum access (DSA) applications, where such forecasting would be an ideal tool to allow both efficient use of the spectrum and at the same time improve protecting the earth-space downlinks. A (literature) study has been performed in Section II-D how such prediction model can be implemented.

The results may be compared with similar propagation research in the microwave frequency range, but in different terrains [11], [12]. The experience gained in the previous propagation measurement was used in the design described here [8], [9], and uses modern technology to achieve high reliability and excellent measurement accuracy.

The design procedures to arrive at a high-quality propagation experiment are described in this paper. The information provided can be used by other researchers to start or enhance their own propagation measurements, which will contribute to further propagation model improvement.

II. TROPOSPHERIC RADIO WAVE PROPAGATION

To design a propagation measurement system, insights in the expected propagation phenomena is necessary. In this section, these phenomena for the 3.5 GHz band will be presented. Around 3.5 GHz, radio wave propagation occurs in the lowest portion of the atmosphere, called the troposphere [13]. Radio wave propagation for this band can be divided into two categories of possible mechanisms:

1) long-term propagation mechanisms:
   a) line-of-sight (LOS) propagation;
   b) diffraction;
   c) tropospheric scatter.

2) short-term propagation mechanisms:
   a) ducting;
   b) elevated layer reflection and refraction;
   c) rain scatter;
   d) aircraft scatter.

A. Long-Term Propagation Mechanisms

Long-term propagation mechanisms are processes, which cause permanent (continuous) reception of radio signals. The main mechanisms are depicted in Fig. 1.

1) Line-of-Sight (LOS) Propagation: Assuming the earth to be a perfect sphere, both antennas can see each other provided

\[ d < \left( \sqrt{2h_1r} + \sqrt{2h_2r} \right) \]

where \( d \) [km] is the distance between the antennas, \( r \) is the earth radius [km], and \( h_1 \) [km] and \( h_2 \) [km] are the antenna heights at both ends of the path [13]. The earth radius in The Netherlands is approximately 6364 km. For a transmit antenna at 60 m and a receive antenna at 10 m height, this LOS distance is 39 km. LOS propagation has a significantly lower path loss than the other mechanisms shown. Therefore, when the LOS condition is met, this is generally the dominant propagation channel.

For radio waves path loss remains low up to a distance that is approximately 4/3 larger, due to the refraction that occurs in the earth standard atmosphere [13]. For the given example, the distance would become 52 km. This slightly greater distance is often referred to as the “radio horizon.” Propagation over distances larger than the radio horizon are referred to as trans-horizon propagation paths.

2) Diffraction: Objects like mountains, (high) buildings can diffract, bend, radio signals. As a result, these radio signals can travel further than the radio horizon up to 150 km [10]. Diffraction mechanisms generally dominate wherever significant signal levels are to be found beyond the radio horizon [10]. In case of flat terrain, without high buildings, the extended range due this mechanism is expected to be limited.

3) Tropospheric Scatter: The most dominant propagation mechanism beyond the diffraction region is the tropospheric scatter or the so-called troposcatter. Here, path loss increases rapidly with distance, but radio waves can still be received as they are scattered by irregularities in the atmosphere. In most situations, signal levels due to troposcatter are too low to cause interference to other systems. Due to troposcatter, radio signals can travel up to 800 km [15]. In addition, due to the seasonal temperature differences, the median signal strength in summer can typically be 13 to 19 dB higher than in winter season [15].

B. Short-Term Propagation Mechanisms

Short-term propagation mechanisms are processes which cause a temporarily reception (up to hours) of radio signals. The main mechanisms are depicted in Fig. 2.

1) Ducting and Elevated Layer Reflection and Refraction: Radio refractivity depends on pressure, temperature, and humidity [17]. If in higher atmosphere layers, this refractivity decreases, radio signals will bend toward the earth. At first, the radio horizon is extended. This phenomenon is called super refraction; if the decrease in refractivity is stronger,

\[ 1 \text{ km} \quad \text{and} \quad 2 \text{ km} \]
ducts/layers can occur where radio signals are trapped. Also, elevated layers can occur where radio signals are reflected and refracted. Ducts can provide stable propagation with low attenuation. It mainly occurs in coastal areas and over large bodies of water [10], because a rapid decrease in humidity with increasing height is required to create a trapping layer [18]. Ducts can exist on ground level (evaporation ducts and surface ducts) or higher up to several kilometers (elevated ducts). For more information on these types, the reader is referred to [18]. In our measurements, ducting can occur up to several hours and can enhance the temporarily reception of radio signals with more than 60 dB.

2) Hydrometeor Scatter: Rain showers can scatter radio signals forward and backward. This is called hydrometeor scatter or rain scatter. It only occurs at microwave frequencies. In most cases, this interference is only very short term and only occurs when the rain shower passes by. In case of fast moving rain drops, a Doppler shift in the radio signal can be introduced as well. Hydrometeor scatter can be up to a few hundred kilometers, but in most situations the signal increase is limited [10].

3) Aircraft Scatter: Aircrafts flying in the sky can scatter or reflect radio signals. This can cause momentary propagation up to 500 km. Due to the speed of the aircraft a Doppler shift of typically several hundred Hertz’s is introduced in received signals. Moreover, this phenomenon is very short and only lasts less than a minute as the aircraft is moving fast. In our measurements, aircraft scatter typically enhances the temporarily reception of radio signals with 10–15 dB.

C. Summary of the Phenomena

Each of these phenomena can be seen as a parallel channel between transmitter and receiver, as shown in Fig. 3. The path loss of each channel, except for the LOS channel, varies independently over time, and each propagation phenomenon is subjected to its own set of input parameters. In the described measurement setup, the dominant long-term phenomenon is tropospheric scatter and short-term mechanisms consist primarily of ducting and elevated layer reflection/refraction.

An example how the path loss behaved during the measured time is depicted in Fig. 4. Here, the path loss of one of the longest paths in the measurement campaign: (Goes, see Fig. 5) has been depicted for the whole measurement campaign. One can see the large fluctuations, both short term and long term in the measured path loss. The difference between the maximum and minimum path loss is more than 90 dB during the measurement campaign.

D. Prediction Models for Occurrence of Anomalous Propagation

The dominant sources of (short-term) anomalous propagation are ducting, super refraction and reflection/refraction of radio signals in elevated layers. These phenomena are caused by similar weather conditions in different altitudes; the atmosphere in the lowest several hundred meters above ground. Predicting such conditions is therefore very important to minimize interference and malfunctioning of wireless systems on the same frequency, especially for DSA systems. Also, in radar applications this is an active topic of research as anomalous propagation will result to contamination of radar data. For more information, the reader is referred to [19] and [20].

Radio refractivity depends on pressure, temperature, and humidity [17]. If in higher atmosphere layers this refractivity decreases, radio signals will bend toward the earth.

The radio refractivity can be calculated using this formula [20]

$$ N = 77.6p/T + 3.73\times10^5e/T^2 $$ (2)
where $p$ is the barometric pressure in millibars, $e$ is the partial pressure of water vapor in millibars (humidity), and $T$ is the absolute temperature in Kelvins.

Especially, the vertical gradient of the refractivity within the lowest several hundred meters above ground is important as most anomalous propagation occurs in these layers.

Four different modes can be distinguished [20].

1) **Sub-Refraction:** \( \frac{dN}{dh} > 0 \text{ km}^{-1} \).
2) **Normal Refraction:** \(-79 < \frac{dN}{dh} < 0 \text{ km}^{-1}\) (typ. \(-40 \text{ km}^{-1}\)).
3) **Super Refraction:** \(-157 < \frac{dN}{dh} < -79 \text{ km}^{-1}\).
4) **Ducting/Trapping:** \( \frac{dN}{dh} < -157 \text{ km}^{-1} \).

This means that for predicting anomalous propagation a weather prediction model is required, which can predict the vertical gradient of the radio refractivity; especially in the lowest several hundred meters above ground. Regular weather forecast models can be used for this purpose, although typically it provides limited vertical resolution in the lowest layer.

In the next step of the prediction model, the threshold for the different modes can be used to forecast the occurrence of Anomalous Propagation conditions.

### III. PROPAGATION EXPERIMENTAL GOALS

To optimally design the propagation measurement system and the geographical layout of the experiment, first the goals and requirements of the experiment must be defined. The realization of these goals has to be balanced with practical constraints.

#### A. Goals and Requirements

The main goal of the experiment is to obtain statistical information on the path loss on frequencies between 3.4 and 3.6 GHz of different propagation paths, both on land and wetland. At least two, and preferably four, trans-horizon paths with a length between 80 and 300 km must be included in the experiment. To evaluate cumulative interference, the simultaneous occurrence of anomalous propagation on different propagation paths has to be measured. The measurements must encompass all seasons and preferably several years. Sufficient measurements must be collected to include propagation phenomena with a low probability of occurrence (<0.1%) that produce a high level of interference. A wireless channel has a coherence time; in this time window the channel can be considered as static. In order to have a new realization for each measurement sample, the period between two samples should be larger than this coherence time, i.e., the measurement samples must be uncorrelated in time.

### B. Nice to Haves

As was explained in Section II-C, several propagation mechanisms may occur independently and at times simultaneously, together producing the statistical distribution of the propagation path loss. If the measurements would allow discrimination between these propagation mechanisms, this would provide additional insight. Provisions for additional measurements must be provided to allow for the investigation of unpredicted propagation phenomena.

#### C. Accuracy and Availability

Targeted overall path loss measurement error was to be as low as possible, but in any case less than ±2 dB (95% confidence). The measurement error is caused by inaccuracies in different components of the system. The total measurement error can be calculated using the components’ inaccuracies and standardized methods. The measurement system must run with as little system failure as possible, to achieve continuous time coverage. Targeted overall availability should be better than 95% and outage intervals should always be as short as possible.

### IV. EXPERIMENTAL DESIGN

#### A. Configuration Alternatives and Choices

In the project, it was key to measure the path loss of two different types of paths: one land path that travels over sand soil and the other path traveling over clay soil and over a large lake (IJsselmeer). The latter can be considered as a wetland path. Furthermore, the paths should be of roughly equal length to allow comparison. In addition, two extra path losses should be measured roughly at the middle of both paths. With this arrangement the correlation of the received signal strength of two nonaligned paths of comparable length, and of two aligned paths of dissimilar length, can be studied. Of course all paths should be longer than the radio horizon in order to measure trans-horizon propagation.

For measuring the path loss, it was decided to use a single receiver and four beacon signals. This simplifies the measurement setup, as at only one location—the victim in practical situations—data needs to be received and recorded. It also
serves monitoring of the measurement. Moreover, the measurement accuracy is improved as well, in comparison to a separate transmitter-receiver setup per path, because in this case the same (calibrated) equipment is used for measuring all paths. Due to the close vicinity and accessibility of all locations, it was decided not to add redundancy in the receivers and transmitters. For data storage, RAID-1 mirroring has been used where also periodically data was transferred via internet to our main office as backup.

Initial path loss calculations indicated that path loss could vary between 140 and 220 dB. The whole measurement setup of beacons and receiver should be designed to cope with this dynamic range. This involves that the weakest signal level should be above the noise floor of the receiver. On the other hand, strong received signals should not saturate the receiver or (potentially) produce intermodulation products on other beacon frequencies.

B. Measurement Resolution, Density, Accuracy, and Duration

The wanted total measurement uncertainty should be ±2 dB or less for the whole measurement setup. A larger uncertainty would degrade the result too much and less uncertainty is always desirable, but more difficult to achieve in practical situations. In Section V-H, the measurement uncertainty of the total system has been calculated, which shows that we have achieved our uncertainty requirement. To study the effects of yearly seasons, it was decided to measure the path loss for three years. Doing so, each season can be measured multiple times.

In most applications, the signal strength of interfering systems on the same frequency is not allowed to exceed a certain threshold in time. A typically used value is 0.005%, which was also the minimum goal to assess in this measurement campaign. To measure this accurately (99%), at least 100,000 measurements are needed. If one assumes that such an event can happen every month, a measurement is done every 30 s. Typically in a month more than 120,000 measurements will be executed given this interval of 30 s. In this setup, on average 500 MB of raw data per month for all beacon sites will be collected. After finishing the measurement campaign, one can conclude that this 30 s period can be shorter, as storage is no issue these days. A shorter period would allow post processing to study the effect of the measurement period.

In the experiment, the likelihood of some downtime is very high. To ensure a good data set, every failure/down time is documented and the faulty data is removed from the measurement setup. Documenting these down times is very important to achieve a high-quality measurement setup. It is both important for removing invalid data from the data set, but evenly important when analyzing the data.

C. Quality Assurance

To assure quality assurance, the whole measurement setup has been analyzed in advance to make sure that the system has the required technical specifications. In addition, an external scientific sounding board was appointed consisting of staff members of the University of Twente. Its tasks were to ensure the quality of the measurements and to audit the projects results.

V. MEASUREMENT SYSTEM REALIZATION

A. Acquisition of Measurement Locations

The beacon and receiver locations are depicted in Fig. 5. In our experiment, we decided that the two paths should be as long as possible to cover most of the Netherlands. Also, in between two additional locations are needed in order the measure the difference in path loss of two aligned paths. Furthermore, the goal was to measure the path loss at typically broadcast heights. For that reason, four broadcast towers were selected for the experiment: Goes, Roermond, Amsterdam, and Zwolle. The receiver was placed in Burum at a military site. Here, the receive antenna was placed much lower, at 6 m height, which is comparable to a regular satellite interception antenna heights. Table I shows the details of each location. To measure the four paths independently, each beacon has a unique frequency.

B. Path Loss Calculations

Initial path loss calculations were done for each path with the ECC Monte-Carlo analysis tool Seemcat [21], using the ITU-R P.452 model for time values from 90% down to 0.001%. This provided a large set of values, representing the complete dynamic range of the expected path losses. Based on these results, system design could be performed and requirements could be set for antenna gains, beacon transmitter power, and receiver sensitivity. During the course of the measurement campaign, the Seemcat simulation results were used as a reference in relation to the measurement data.

C. Provisional Link Budget Calculations

Knowing the upper and lower limits of the signal strength to be expected, link budget calculations were done to perform the system design of the measurement setup. One of the system’s requirements was the ability to also monitor the beacon signals under normal propagation conditions. For this purpose the transmitted power and the receiver sensitivity should be sufficient to deal with a path loss up to approximately 220 dB. On the other hand, the measurement system should be capable to cope with the relatively strong signals due to anomalous propagation (140 dB path losses, which is 70 dB less than
under normal propagation conditions). Strong anomalous propagation determines the receiver linearity requirements.

The beacons basically consisted of a continuous waveform RF source, a power amplifier and a directional antenna. An equivalent isotropically radiated power (EIRP) of 66 dBm was chosen for the beacons in the two longest paths, whereas for the two beacons closer to the receiver, the EIRP power was 10 dB less.

At the receiver side, a directional antenna, a low-noise amplifier (LNA), and a spectrum analyzer were the basic components. A measurement resolution bandwidth of 100 Hz was selected that resulted in a thermal noise floor of $-130$ dBm. The desired sensitivity of the receiver—set by normal propagation—has been achieved in conjunction with the gains of the antenna and the LNA.

**D. Transmit and Receive Antennas**

Based on Section V-C, a high-gain reflector antenna was selected with a specified 27 dBi antenna gain. In order to determine the antenna gain, this antenna was calibrated by the National Physical Laboratory, U.K. The measured antenna gain was 26.1 dBi $\pm 0.2$ dB (95% confidence interval). This clearly shows that for these kinds of measurements, it is paramount to calibrate the used antennas; otherwise a large measurement error will be introduced.

Besides, antenna gain also the opening angle (3 dB) is very important. In this case, the measured and calibrated opening angle is $8^\circ$ vertical and $6^\circ$ horizontal. See Fig. 6 for the antenna pattern. Measurement errors will be introduced if the antenna is not exactly aligned toward the beacon sites. In this case, the maximum allowed error is typically $1^\circ$ that is neglectable on the measurements.

**E. Measurement Receiver**

The receiver includes four outdoor antennas, of which two directional antennas (26 dBi gain, similar type as the beacon site), one horizontal omnidirectional (11 dBi gain) antenna, and one wide-angle directional patch antenna (5 dBi gain). The first two antennas are used to measure the path loss of the four beacons/two paths. The main purpose of the other antennas is to complement the results. The reason is that some types of anomalous propagation may be received from a different angle than the direction of the beacons itself. With directional antennas, one could easily miss those extraneous signals. Comparison of the directional and omnidirectional measurement data basically shows a rather noisy $\pm 20$ dB range of values. It did not reveal any significant incidental effects where signals were received from a different angle than expected. Nevertheless, the omnidirectional antennas have proven to be very useful for verifying the measured data.

In Fig. 7, the block diagram of the receiver is depicted. Each receive antenna is connected with its own frontend unit (with a 21.5 dB gain and 2.3 dB noise figure), by means of a low-loss coaxial cable (0.8 dB loss). The outputs of the frontends go through coaxial cables (3.3 dB loss) to an RF switch (3 dB loss), which selects one antenna to be connected to the spectrum analyzer, the Rohde & Schwartz FSV3 spectrum analyzer with B14 option. It has a noise floor of $-153$ dBm typ. (Displayed average noise level value) and a dynamic range of 90 dB. Both specifications meet the requirements in dynamic range and sensitivity.

The front-end circuit for each antenna is depicted in more detail in Fig. 8. The used components are also listed in Fig. 8.

At the point where the cables enter the building overvoltage protection is applied (EMP protector (Huber + Suhner 3400/3406), to avoid damage of the equipment due to lightning. The total gain of the receive chain (including antenna) is 40 dB for antennas 1 and 2, 25 dB for antenna 3, and 19 dB for antenna 4. To monitor the performance of the receive chains, each frontend is supplied with a known reference signal, that is inserted immediately behind the antenna connection. As such, the reference signals can be used to compensate for frontend gain variation due to temperature or aging. The reference signal generator has a fixed frequency of 3.448995 GHz and an output power of $-60$ dBm. The specification of frequency
and level stability is $10^{-7}$ and 0.9 dB, respectively. This is a similar Rohde & Schwartz signal generator that has been used at the beacon sites. More details are described in Section V-G.

For each receiver chain, the reference signal is divided and attenuated individually per chain for ease of recognition. Coaxial cables (with an attenuation of 5 dB) carry the reference signals to the frontends. The receiver is controlled by a MATLAB program that initiates a swept measurement of the four beacons. The frequency sweep is done from 3.448990 to 3.449015 GHz (25 kHz span and 501 data points) with a resolution bandwidth of 100 Hz.

Selection between each path is made by the RF switch, which is depicted in Fig. 9. It also lists the used equipment consisting of a Rohde & Schwartz R&S SGS100A (RF signal generator), minicircuits ZHL-16W-43+ power amplifier, minicircuits ZARC-25-63+ Power Sampler, Rohde & Schwarz R&S NRP-Z211 power sensor, and an HD27392 reflector antenna. Its measured and calibrated antenna gain was 26.1 dBi [±0.2 dB (95% confidence interval)].

In order to fully utilize the dynamic range at the receiver, each beacon was configured with its optimal EIRP transmitted power value in such a way that the typical received signal strength of all paths had equal level. Beacon Zwolle was configured to output 56 dBm, Amsterdam 55.9 dBm, Goes 65.8 dBm, and Roermond with 65.9 dBm.

Beacons are installed indoor behind a window. Of course, the values above have been compensated for attenuation by the window at the beacon site. The latter turns out to be very small, 0.06 dB. Furthermore the RF signal generator had installed the R&S SGS-B1 option (Reference Oscillator)

$$y = a + j \times B$$ (a causes attenuation; B causes phase shift) $y = j \times (2 \times \pi \times f \times f \times 10^{6}) \times (Er' - j \times Er'') = 2.2 + j \times 440$ attenuation (dB) $= 20 \times \log(e^{(a \times d)}) = 20 \times \log(e^{(-2.2 \times 0.003)}) = 0.06$ dB.

References for the above:
to allow small frequency errors: $< 10^{-8}$ and deviations in time aging: $< 10^{-9}$/day, and $< 10^{-7}$/year. All values are relative to the RF output frequency.

**H. Measurement Uncertainty**

Both the beacon transmitter as well as the measurement receiver contributes to the overall measurement uncertainty. For determining the measurement uncertainty, the European method EA-4/02 has been applied [22]. At the beacon side, variation in transmit frequency and output power is taken into account. Frequency error of the beacon is tackled at the measurement receiver side, where a frequency sweep across the entire band is done (501 points over 25 kHz), after which the highest signal level within a particular frequency window is determined for each beacon. Output power variation of the beacon transmitter is reduced by a power control loop ($\pm 0.1$ dB). Additional variation in output power might be caused by the uncertainty of the power sensor readout ($\pm 0.09$ dB) and the accuracy of calibration of the antenna ($\pm 0.18$ dB). Other values have been taken from the appropriate datasheets. At the receiver side, the measurement uncertainty is determined by the calibration accuracy of the antenna, the output power variation of the reference source ($\pm 0.9$ dB), and the level measurement accuracy of the spectrum analyzer ($\pm 1$ dB). All values have been taken from the appropriate datasheets. In addition, the contribution of the splitter and the attenuator in the reference signal path has been taken into account. The combination of all the contributions results in an overall uncertainty of 1.5 dB.

**I. Quality Assurance**

Several checks have been implemented at both the beacons and measurement receiver to safeguard continuity of experiment by determining the uptime of the equipment. Under normal operating conditions, an e-mail message is send once every day to the administrator to indicate that the equipment is up and running. In addition, both the performance of the beacons and measurement receiver are monitored on an hourly basis. In case, the beacon output power or the signal level of the receiver reference signal exceeds predefined tolerance limits, an e-mail message is send to the administrator.

**J. Data Storage**

Measurement data are stored locally on a PC and uploaded once every day onto an NAS storage facility at the office location. The same procedure is followed with respect to the beacon output power monitoring data. Each month, data from the server are processed cumulatively, using a MATLAB script. For each beacon path, a data file is used, which includes raw received signal power and calculated path loss versus time. In addition, for each receiver channel a file including reference signal values is maintained. The latter ones are used to correct the path loss figures of the beacon paths, as to remove gain variation of the receiver setup.

**VI. Comparison of the Results With ITU-R P.452-16**

Fig. 11 depicts the path loss cumulative density function (CDF) of the four beacon signals for the whole measurement period of three years. The dashed lines are the predicted CDF’s according to ITU-R 452. The CDF gives the area under the probability density function from minus infinity to a specific point in Fig. 11.

From Fig. 11, one can derive that in general the ITU-R 452 estimated curves are higher than the actual measured CDF lines. This is also expected as the ITU recommendation calculates a worst case estimation of the path loss. Second, one can
TABLE II
ANNUAL STATISTICS OF THE MEASURED PATH LOSS

<table>
<thead>
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<tr>
<td></td>
<td>Roermond-Burum</td>
<td>221.1</td>
<td>239.0</td>
<td>158.0</td>
<td>81.0</td>
<td>6.3</td>
</tr>
<tr>
<td>2015</td>
<td>Amsterdam-Burum</td>
<td>204.1</td>
<td>228.8</td>
<td>139.6</td>
<td>89.2</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>Zwolle-Burum</td>
<td>203.2</td>
<td>228.2</td>
<td>141.7</td>
<td>86.5</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>Goes-Burum</td>
<td>218.4</td>
<td>238.4</td>
<td>143.2</td>
<td>95.2</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>Roermond-Burum</td>
<td>220.7</td>
<td>238.1</td>
<td>149.0</td>
<td>89.1</td>
<td>6.6</td>
</tr>
<tr>
<td>2016</td>
<td>Amsterdam-Burum</td>
<td>203.8</td>
<td>227.2</td>
<td>137.3</td>
<td>89.9</td>
<td>10.3</td>
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<tr>
<td></td>
<td>Zwolle-Burum</td>
<td>202.4</td>
<td>227.4</td>
<td>141.4</td>
<td>86.3</td>
<td>10.5</td>
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<tr>
<td></td>
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<td>238.1</td>
<td>157.0</td>
<td>81.1</td>
<td>7.0</td>
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</table>

Fig. 13. Availability of path loss data for the four beacons: Amsterdam-Burum (red), Zwolle-Burum (blue), Goes-Burum (purple), and Roermond-Burum (green).

In addition, the measured data are presented also in different formats. Table II shows statistics of the measured path loss, and in Fig. 12 the median monthly path loss has been displayed. From Fig. 12, one can distinguish the seasonal pattern in path loss due to temperature difference, where during summer season a lower path loss exists. Also the seasonal difference is larger for the two shortest paths.

In Fig. 13, the monthly uptime for each beacon is displayed. On average, the downtime of a beacon is 2% to 3%. Due to the problems in Section V-L, there were a few months with larger downtime; especially the seventh month. Overall the uptime was sufficient for the experiment.

VII. PROPAGATION OBSERVATIONS

In this section, some interesting propagation observations are presented. First, in Fig. 14 an example of ducting is shown where all beacon signals are received simultaneously up to 50 dB stronger. Furthermore, in Fig. 15, an example of rain scatter is depicted of a passing storm front. Fig. 16 shows the accompanying weather radar plot of the passing front.

Finally, in Fig. 17, the occurrence of aircraft scatter is presented. South of beacon Amsterdam, Schiphol airport is located; a major European hub of passenger flights. In addition, a smaller regional airport (Rotterdam airport) is located roughly 45 km south of Schiphol. Its location is in the path Goes-Burum too. The marked red dots are path losses which can be attributed to aircraft scatter; the path loss is in this case 10–15 dB less and a Doppler shift occurs of at least 100 Hz compared with neighboring measurement points. From Fig. 17, one can conclude that aircraft scatter occurs regularly in case of nearby airports. However, due to the short period of occurrence, its influence on the CDF is very limited. In addition, we have observed that in the path loss of beacon Amsterdam less aircraft scatter has been detected, probably because this path is entirely north of the airport.

VIII. OTHER EXPERIMENTS

A. Correlation in Path Loss in Case of Anomalous Propagation

The 3.4–3.8 GHz frequency band will be used in the future by BWA devices with many different transmitter (base station) locations. For predicting the (total) interference level received at the existing earth-space downlinks in Burum, it is vital to know whether these anomalous propagations occur over a large part of the Netherlands, or need to be modeled as uncorrelated
interference sources. In Table III, the correlation between the paths losses of the four beacon signals is listed.

If anomalous propagation occurs in one receiver path, it is determined if this is also true for the other signals at the same time. A threshold of 0.1% (in the CDF) has been chosen, in order to analyze only strong Anomalous Propagation occurrences. More research could be allocated to find more sophisticated approaches. From Table III, it can be seen that the signal from beacon Roermond differs from other signals; there is less correlation with anomalous propagation events in other signal paths. Basically, it displays the difference between land and wetland paths. Zwolle is also on the land path, but relatively close to the lake IJsselmeer. (The IJsselmeer is a former sea; parts of it have been converted to land. Zwolle is located around 15 km from the old coastline.) Finally, Table III concludes with both a sum of the three individual correlations and a combined correlation number “Any beacon.”

### Table III

<table>
<thead>
<tr>
<th></th>
<th>Amsterdam</th>
<th>Goes</th>
<th>Zwolle</th>
<th>Roermond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam</td>
<td>-</td>
<td>13%</td>
<td>13%</td>
<td>2%</td>
</tr>
<tr>
<td>Goes</td>
<td>21%</td>
<td>-</td>
<td>16%</td>
<td>10%</td>
</tr>
<tr>
<td>Zwolle</td>
<td>16%</td>
<td>13%</td>
<td>-</td>
<td>6%</td>
</tr>
<tr>
<td>Roermond</td>
<td>4%</td>
<td>11%</td>
<td>9%</td>
<td>-</td>
</tr>
<tr>
<td>Sum</td>
<td>41%</td>
<td>37%</td>
<td>38%</td>
<td>18%</td>
</tr>
<tr>
<td>Any beacon</td>
<td>32%</td>
<td>30%</td>
<td>28%</td>
<td>15%</td>
</tr>
</tbody>
</table>
shows the percentage of anomalous propagation occurrences that are correlated with any of the beacons. The difference between both numbers indicate how correlated the Anomalous Propagation events are in different beacon signals.

Table III shows that for the beacon signal Roermond 15% of the anomalous propagations, also occur at the same time at other sites. For the three other beacons this percentage is around 30%. Also Table III reveals that for these beacon signals, the probability is higher that such conditions occur at multiple beacon signals compared to the Roermond signal, i.e., the difference between the sum and any beacon value is much lower for Roermond.

B. Path Loss Difference Between High and Low Beacons

Mobile networks use lower antenna heights than the beacon heights used in this experiment. In order to study the difference in path loss, in the summer of 2016 a second beacon was installed in Amsterdam at an antenna height of 55 m. (The first beacon has an antenna height of 107 m.) The lower beacon was located on a high apartment building, at the north-east border of city where no other high buildings were in the vicinity that could block the signal toward Burum. The beacon location of both beacons in Amsterdam and path to Burum is shown in Fig. 18. The distance between both beacons is around 8 km.

In Fig. 19, the distribution of the path loss difference is depicted. (The difference of both path losses at the same time.) It is a discrete version of a probability density function. As expected, one can see that both path losses are independent as the resulting CDF resembles a log-normal distribution. The median signal difference is about 0.5 dB due to the lower antenna height and a slightly shorter path of the second beacon.

C. Hour of the Day and Occurrence of Anomalous Propagation

Finally, it was analyzed at which hour of the day anomalous propagation occurred. For this, the same threshold of 0.1% in the CDF has been applied (Section VIII-A). The result has been depicted in Fig. 20. It shows clearly that for three paths (Amsterdam, Zwolle, Goes) predominantly the occurrences are in the evening till early morning hours. Path Roermond is different, which confirms that other anomalous propagation mechanisms are dominant in this path.

The result of Fig. 20 is very important for the intended usage of the 3.5 GHz (5G mobile networks). Interference to the earth-space downlink could, for instance, be reduced by limiting the usage of this band in the evening till early morning hours. In this time window, typically, mobile networks are not used much and mobile operators could migrate the remaining users to other frequency bands. Fig. 21 depicts the CDFs of all path losses if only the time window 9–21 h is taken into account. It can be seen that the resulting CDF is shifted to
the right, typically 5 dB or more for the probability region of interest $10^{-5}$ to $10^{-4}$.

IX. CONCLUSION

In this paper, the design and realization of a high accuracy 3.5 GHz trans-horizon radio propagation measurement system have been presented. The realized setup meets the requirements set in the design phase. During three years (September 2013–November 2016), this system has successfully collected the path loss of two different paths; a land path and a wetland path. The measurements reveal that the ITU-R 452 estimated curves typically show up to 5 dB higher path loss than the actual measured CDF lines for the probability region of interest $10^{-5}$ to $10^{-4}$. This is also expected as the ITU recommendation calculates a worst case estimation of the path loss. However, for the wetland, the measured CDF is (unexpected) very close to the estimated one or even slightly higher. Moreover, on each path, an additional transmitter has been placed to study the correlation between anomalous propagation in aligned and unaligned paths. This is important for modeling interference from a mobile network consisting of hundreds of base stations. Our measurements reveal that typically 30% of the anomalous propagation occurrences are correlated with other beacon signals. (So 70% of the cases are uncorrelated.) In case of the land path, this percentage is 15%. In addition, the results show that predominantly anomalous propagation occurs in the evening till early morning hours.

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REFERENCES


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Prof. Bentum is a Chairman of the Dutch URSI Committee, the Vice Chair of the IEEE Benelux section, the Initiator, and the Chair of the IEEE Benelux AES/GRSS chapter, and has acted as a reviewer for various conferences and journals.

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From 1995 to 1996, he was a Research Assistant of signal processing for mobile telecommunications and medical data processing with the University of Twente. In 1996, he joined the Netherlands Foundation for Research in Astronomy where he was in various positions. In 2005, he was involved in the eSMA Project, Hawaii to correlate the Dutch JCMT mm-telescope with the Submillimeter Array of Harvard University, Cambridge, MA, USA. From 2005 to 2008, he was responsible for the construction of the first software radio telescope in the world, low frequency array. In 2008, he became an Associate Professor with the Telecommunication Engineering Group, University of Twente where he was also the Program Director of electrical engineering, from 2013 to 2017. In 2017, he became a Full Professor of radio science. He is currently involved with research and education in radio science. His current research interests include radio astronomy, short-range radio communications, novel receiver technologies (for instance in the field of radio astronomy), channel modeling, interference mitigation, sensor networks, and aerospace.

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